Top quark measurements with ATLAS

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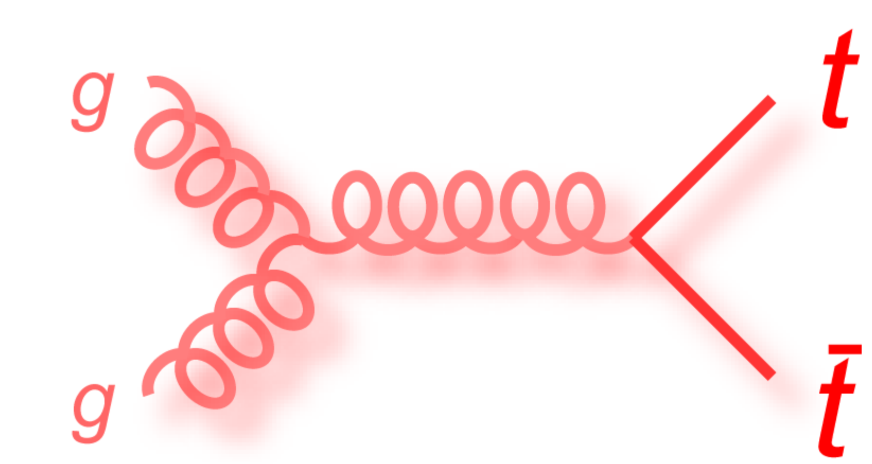
ROYAL HOLLOWAY UNIVERSITY OF LONDON

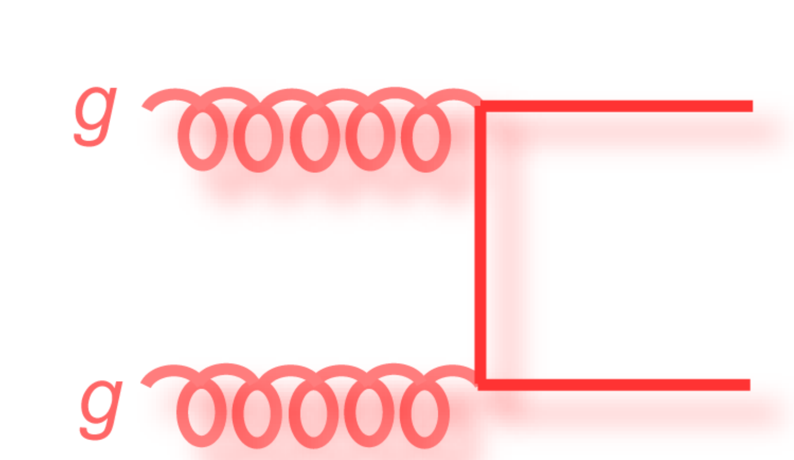
ATLAS EXPERIMENT

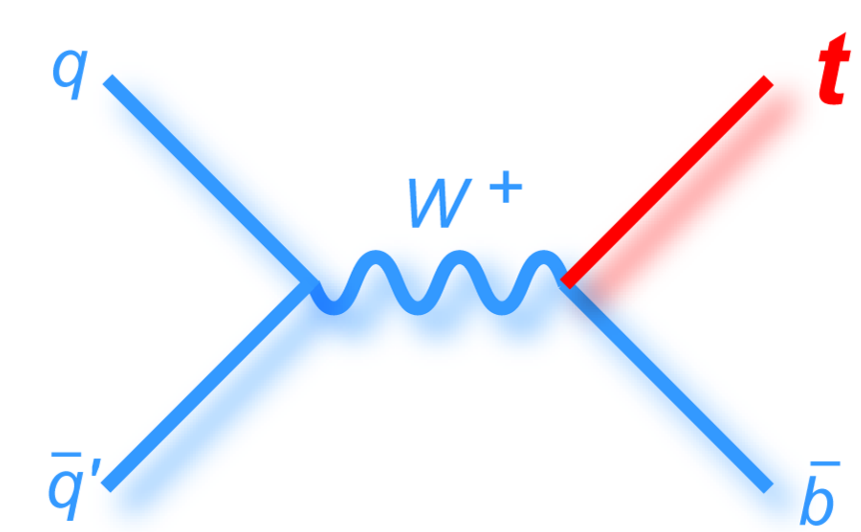
Why study the top quark?

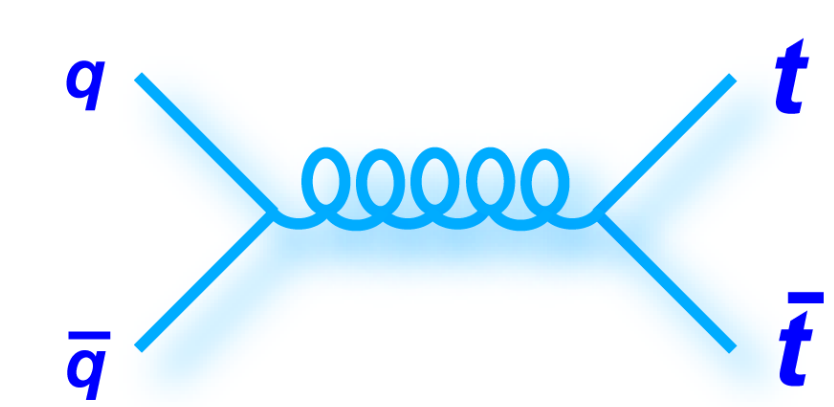
- Heaviest SM particle (172.5 GeV)
  - Role in vacuum stability, Higgs sector
  - Background to exotic searches, Higgs measurements
- Decays before hadronisation
  - We can study a ‘bare’ quark
  - Allows precision QCD measurements
- Window into new physics
  - Same magnitude as ϕ vev (v = 246 GeV)

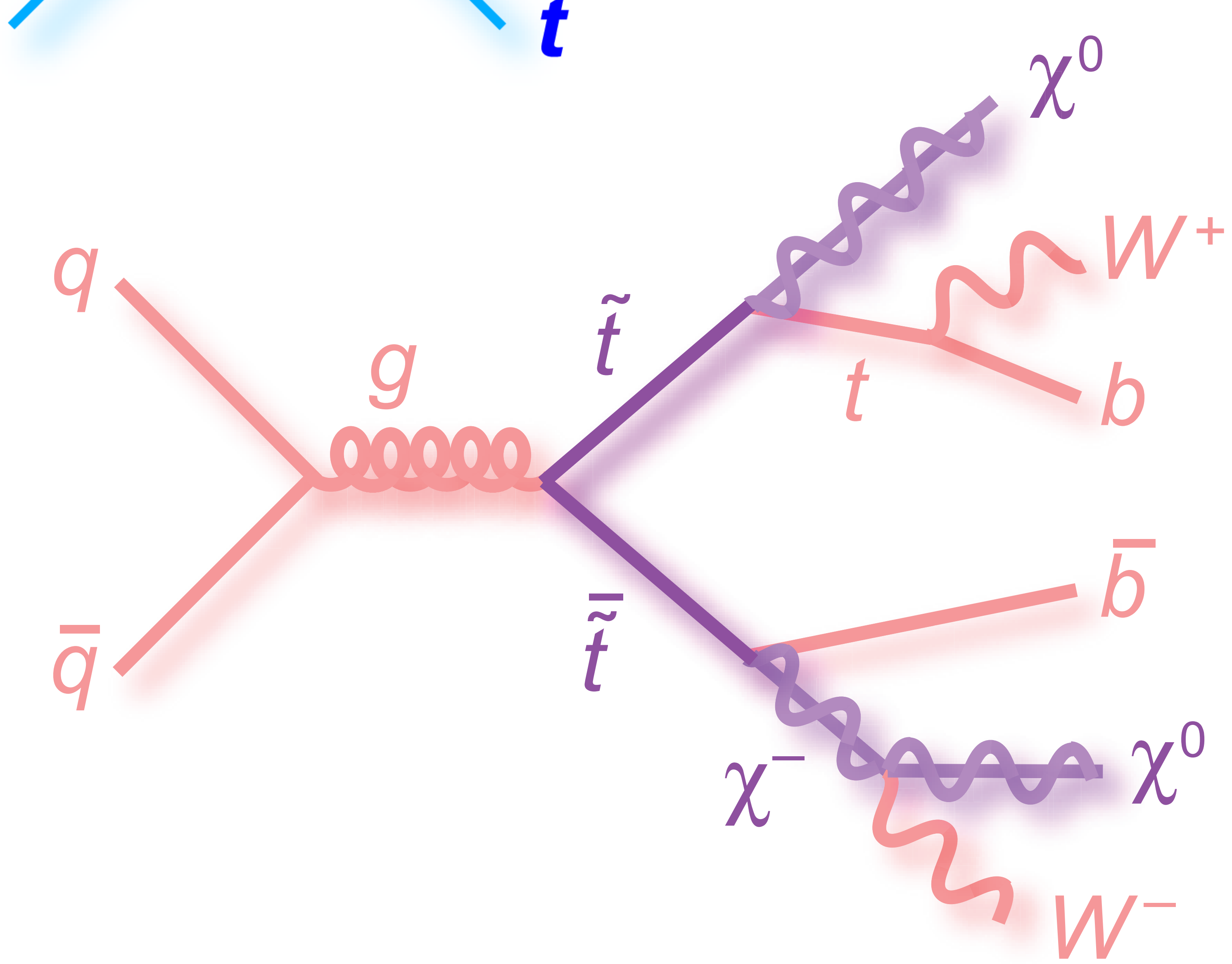
$$m_t = y_t v/\sqrt{2}$$





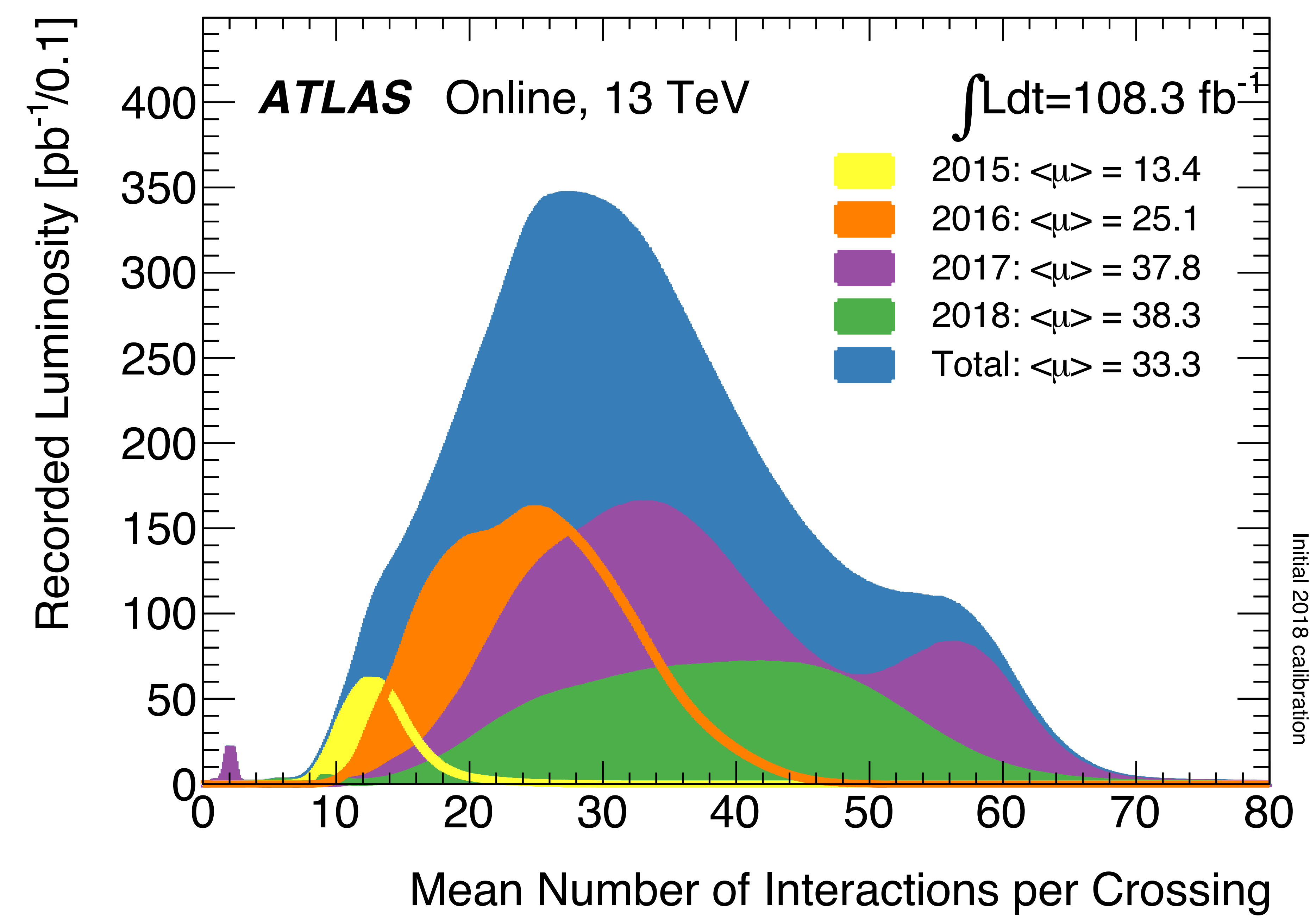






Status

- LHC Run 2 @ 13 TeV is going very well
  - 130 fb^{-1} delivered to date, 3.2 fb^{-1} in 2015, 36.1 fb^{-1} recorded by ATLAS in 2015+16
  - Approximately 1 tt pair produced each second
- Very active area of ATLAS's research programme
- Precision measurements now reaching <1% uncertainty
  - Critical feedback for next-gen MC generators
  - Useful for theorists: contraining EFTs, gluon PDF for large x, NNLO corrections



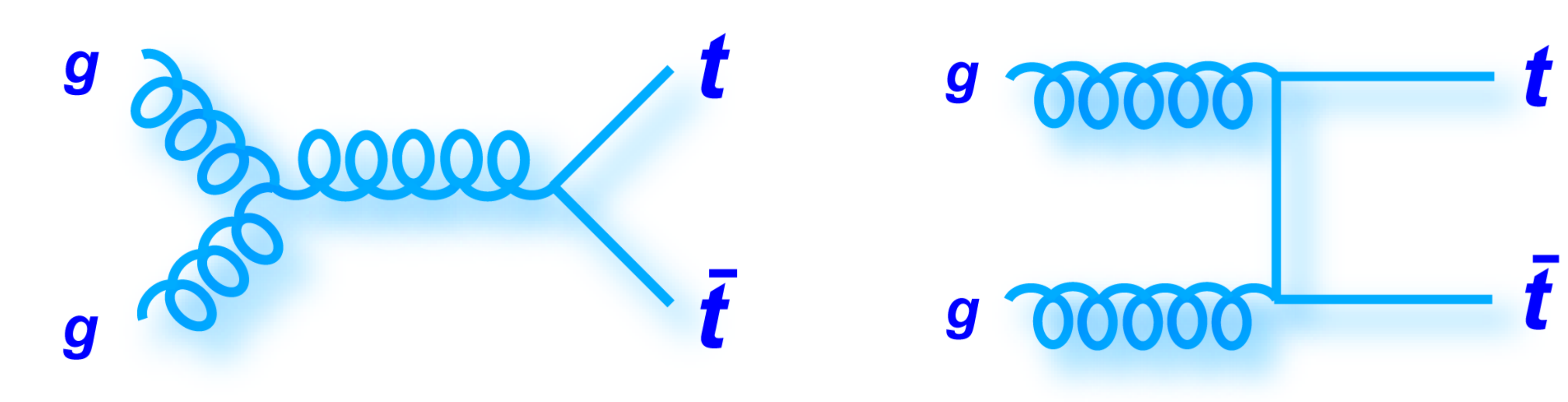
ATLAS top physics programme

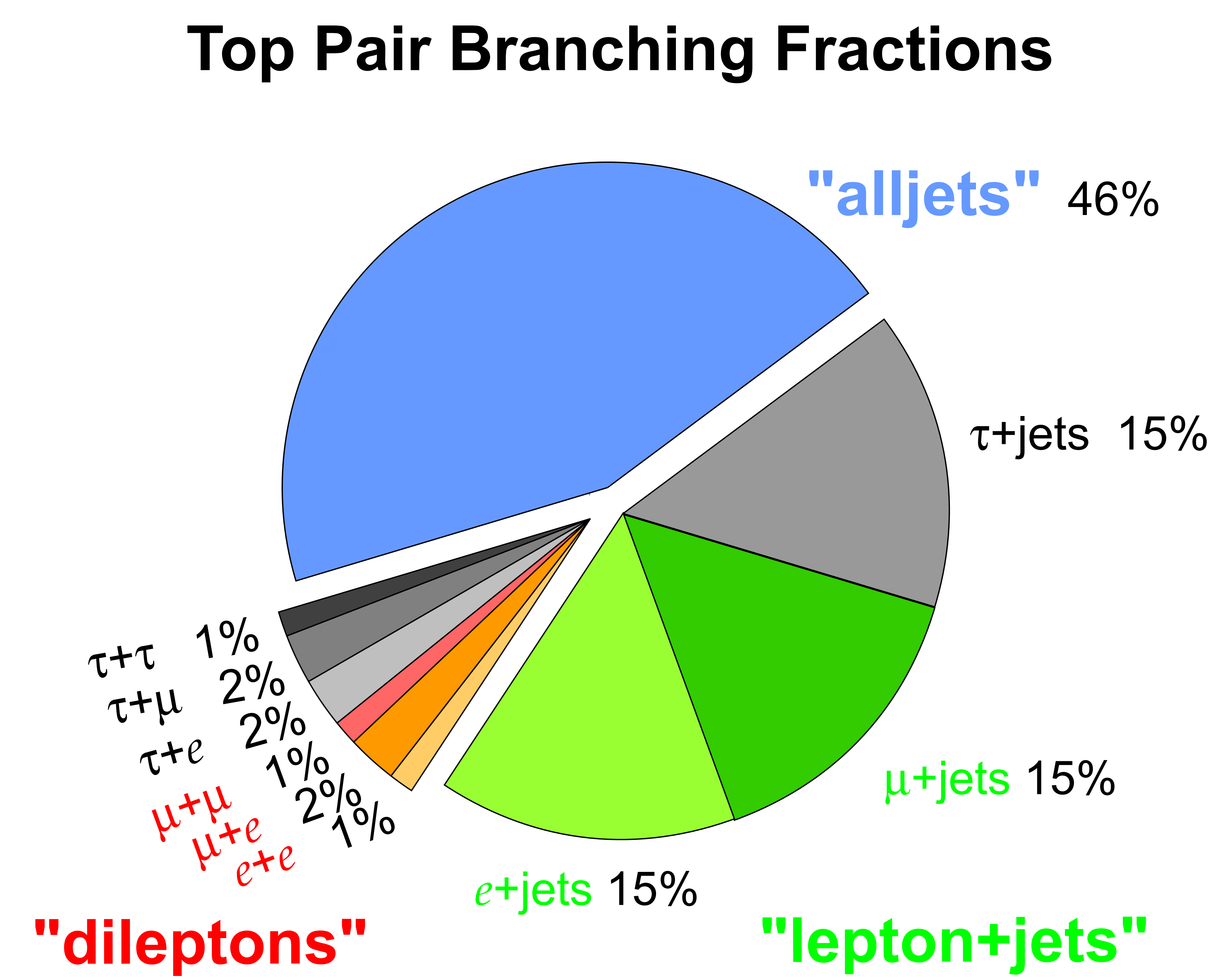
- ATLAS has a rich top physics research programme — link to public results
- tt, tt+X: differential cross sections in many variables, many 2D differential results
    - Unfolding to both particle and parton levels
- Single top, t+X
- Top quark mass and properties
- Advanced analysis techniques used throughout for increasingly precise measurements

- So much I could talk about. This talk gives an overview of each area, focuses on ~~my favourite~~ some specific analyses, with emphasis on analysis methods

tt cross sections — motivation

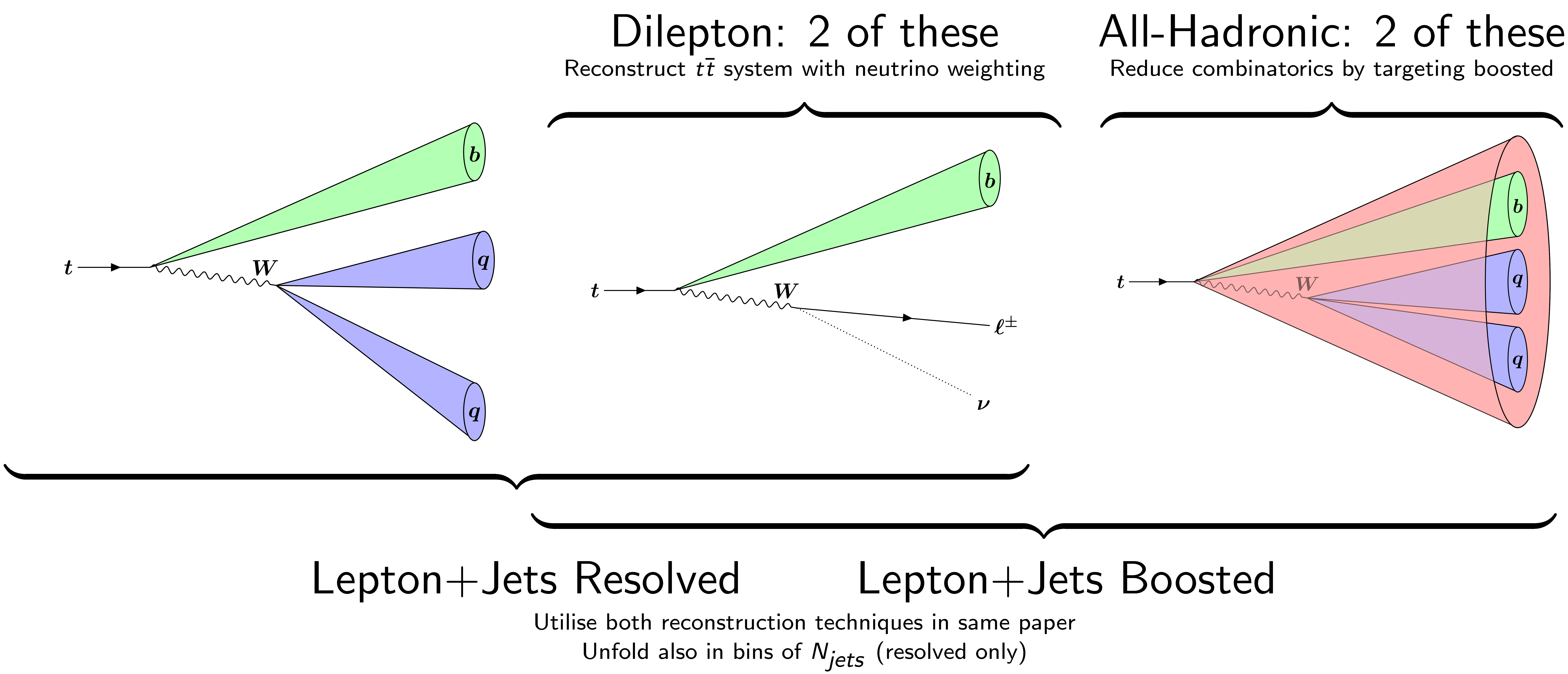
- Cross sections are measured differentially
- Theoretical motivation: constraining EFTs, gluon PDF at high x, test predictions at highest precision
- tt(+X) is highly sensitive to BSM physics
- Major background to SM (e.g. ttH), exotic, SUSY searches
- Top modelling / MC tuning
    - Top p_T has been poorly described by some generators
- A range of final states separate our analyses





tt cross sections — analysis channels

- Top quark decays t→Wb

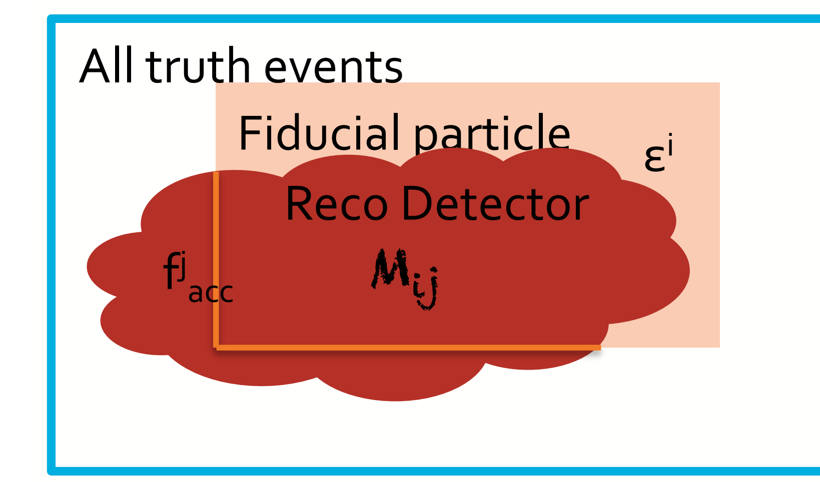


Diagrams courtesy M. Fenton

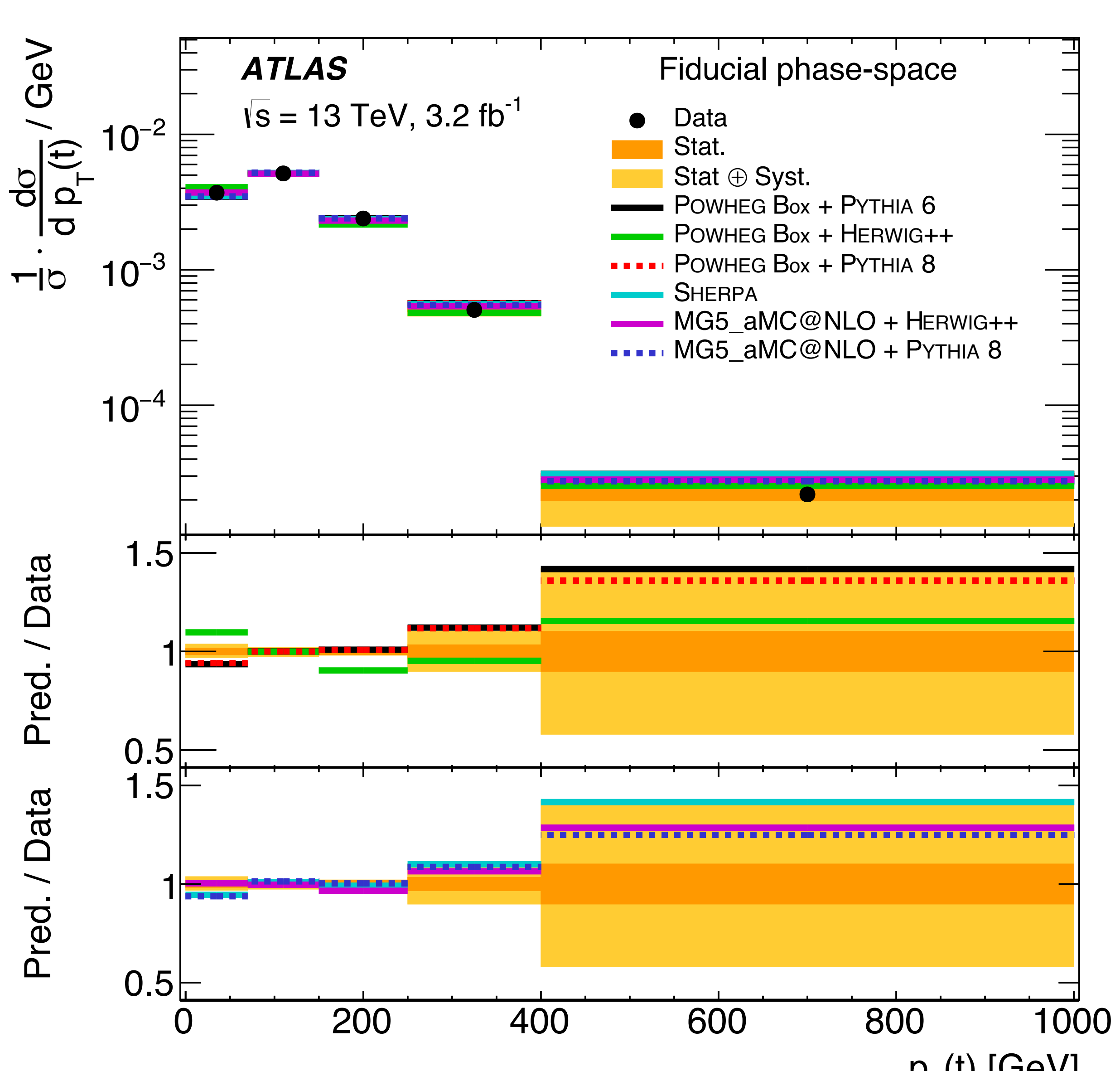
tt cross sections — summary

- All analyses share common unfolding strategy to fiducial volume at particle level
  - Some also unfold to parton level
  - 2D unfolding increasingly possible

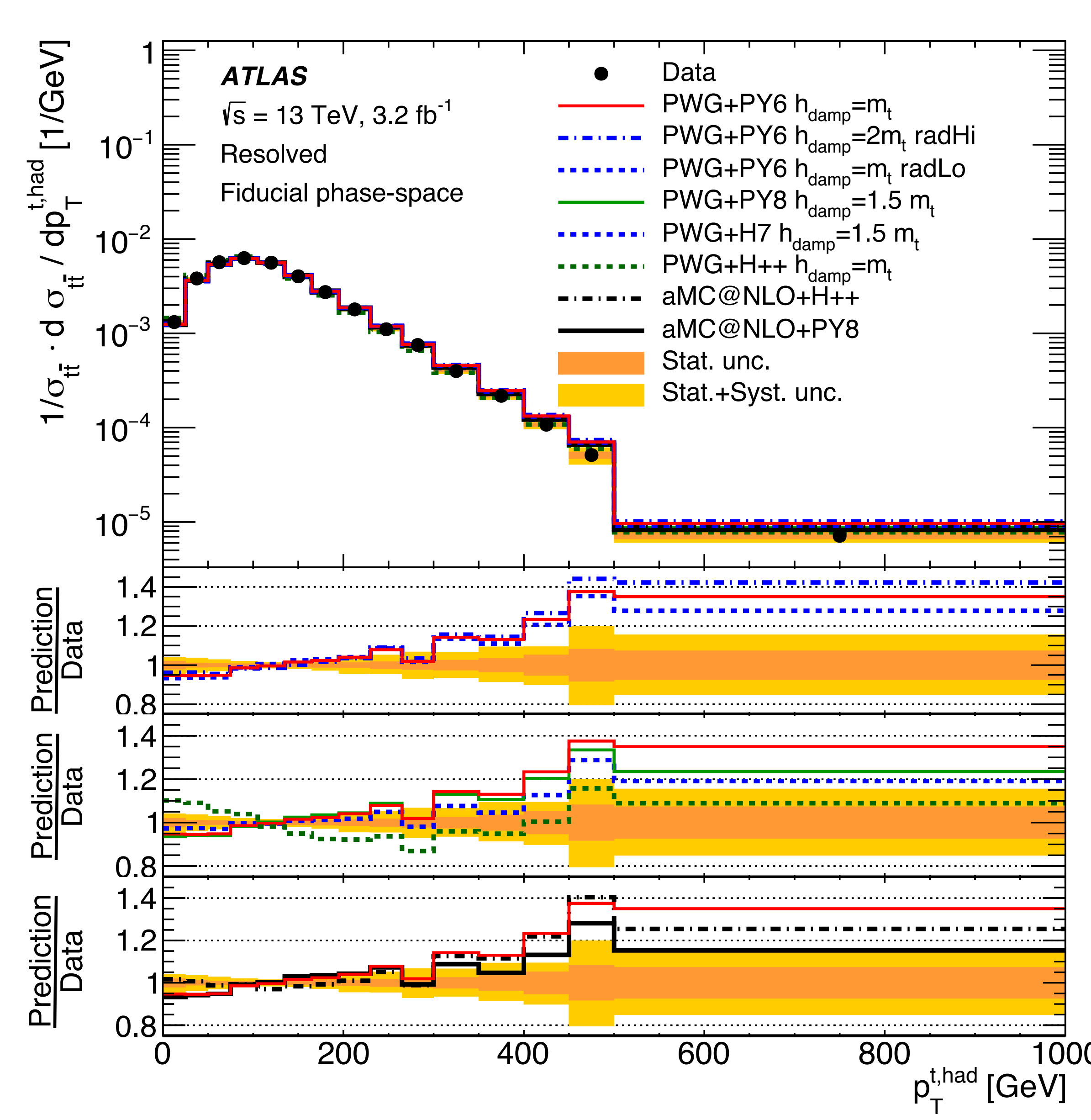
$$\frac{\mathrm{d}\sigma}{\mathrm{d}X_i} \equiv \frac{1}{L\cdot\Delta X_i\cdot\epsilon_i}\sum_j M^{-1}_{ij}\, f_j^{\mathrm{acc}}\left(N_j^{\mathrm{reco}} - N_j^{\mathrm{bkg}}\right)$$



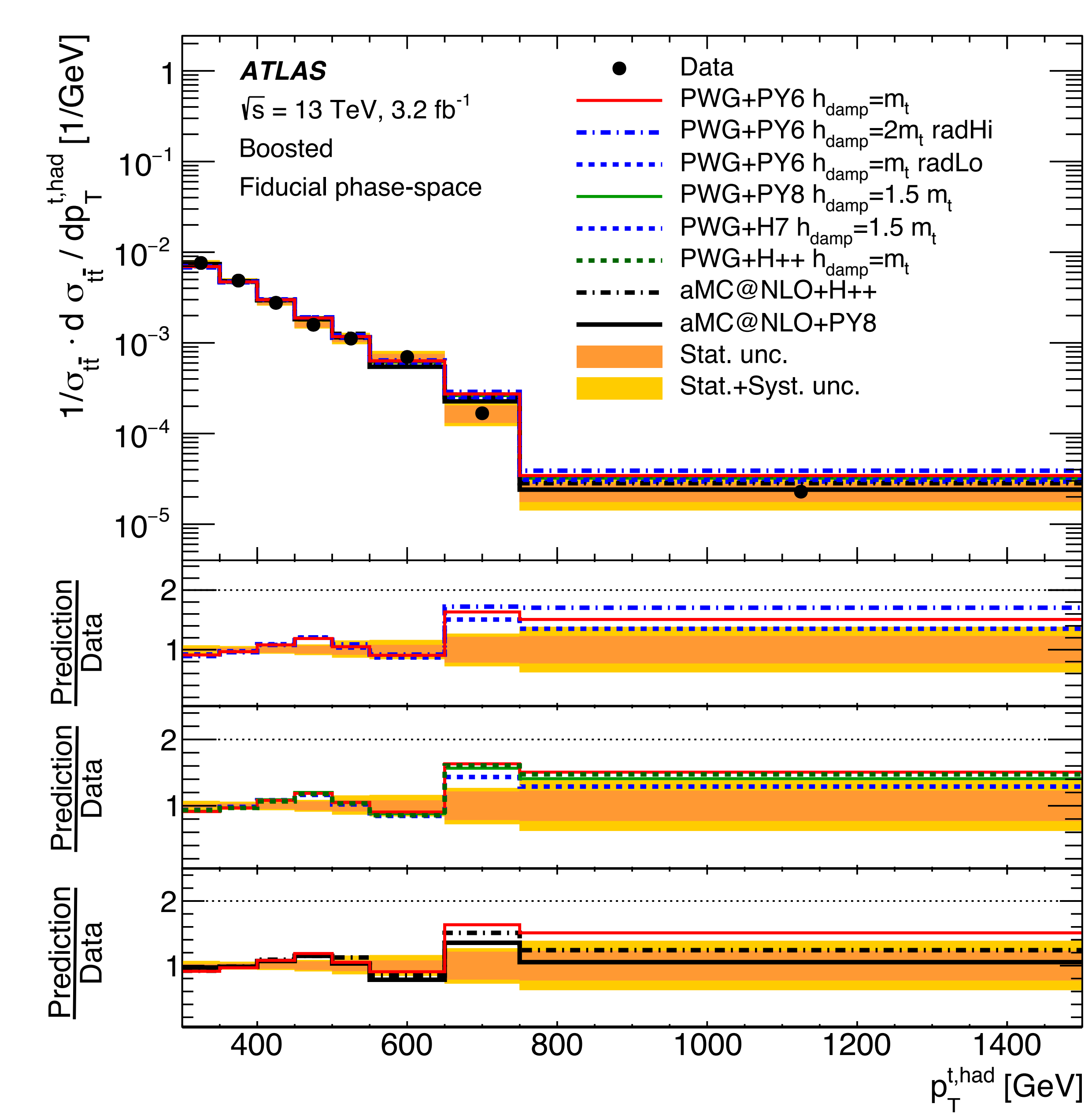
- Systematics dominate uncertainties: top modelling (matrix element, parton shower), jet energy scale/resolution



Dilepton: paper



l+jets resolved: paper

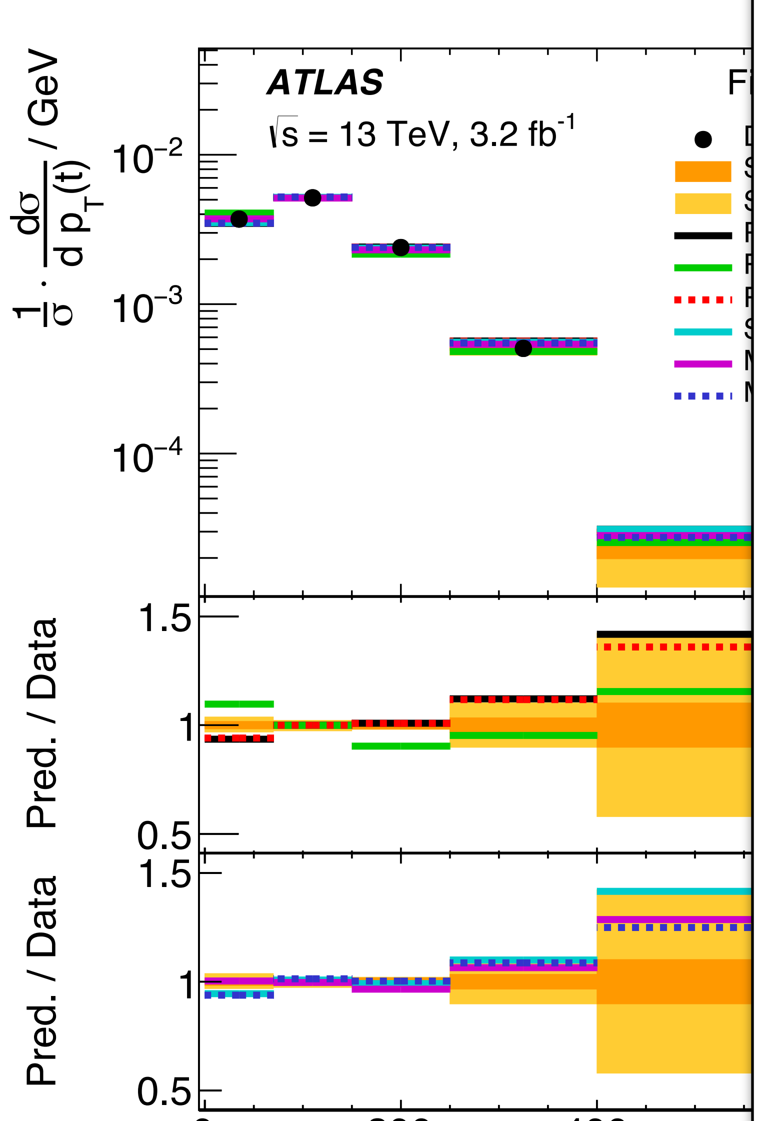


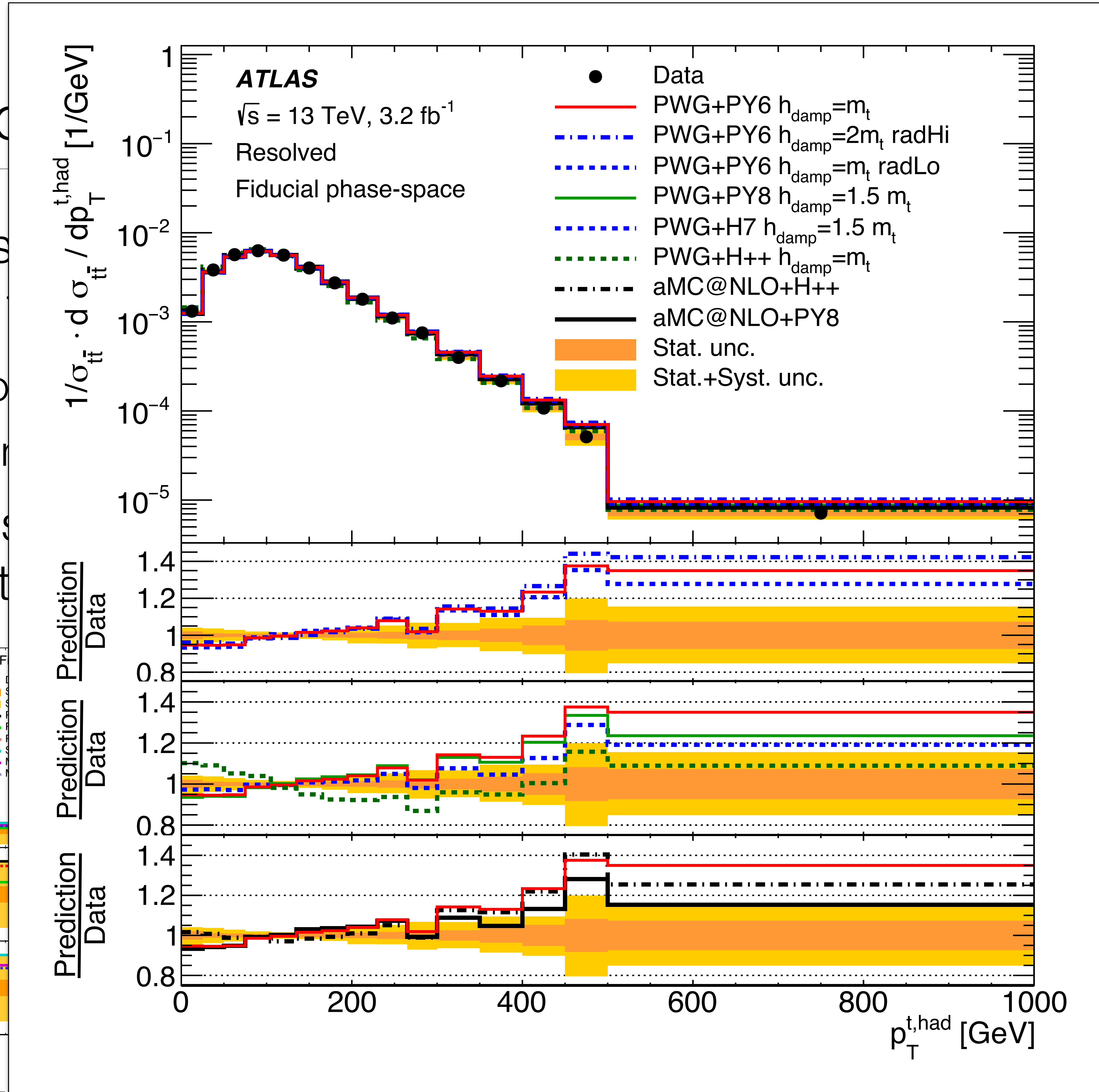
l+jets boosted: paper

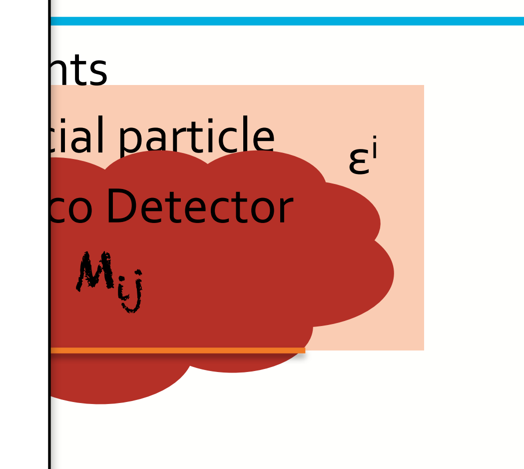
tt cross sec

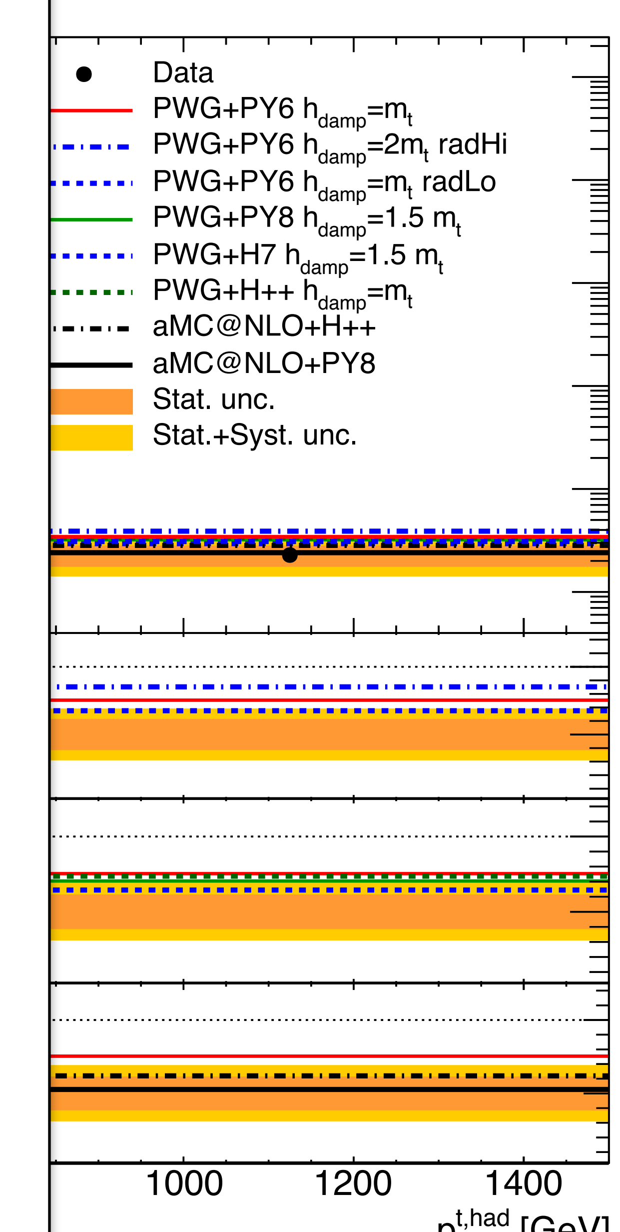
- All analyses
  strategy to
  - Some also
  - 2D unfoldi
- Systematics ... ent, parton
  shower), jet

$c \left(N_j^{\mathrm{reco}} - N_j^{\mathrm{bkg}} \right)$



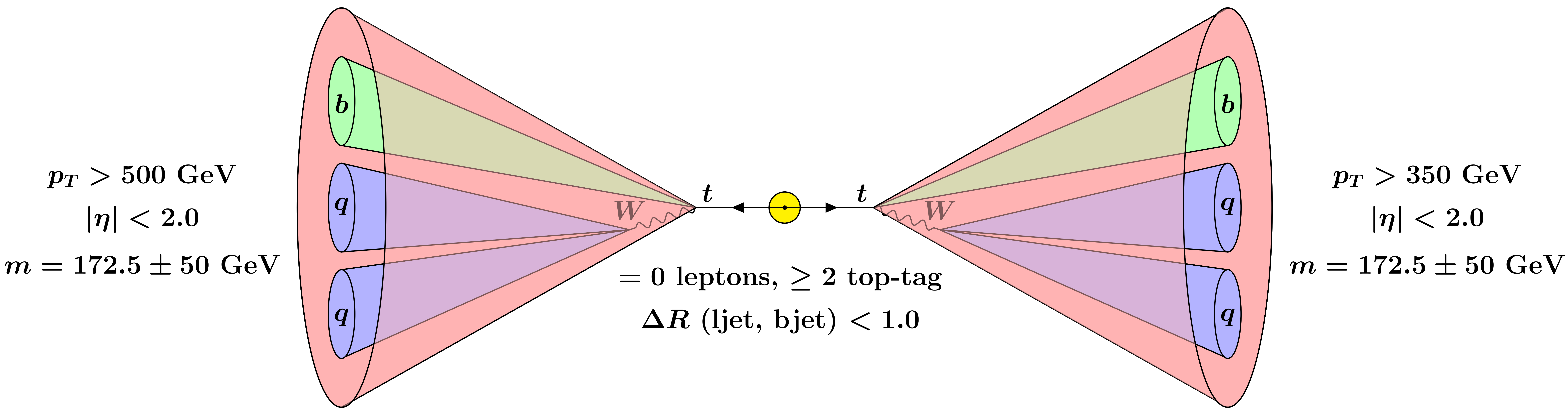






l+jets boosted: paper

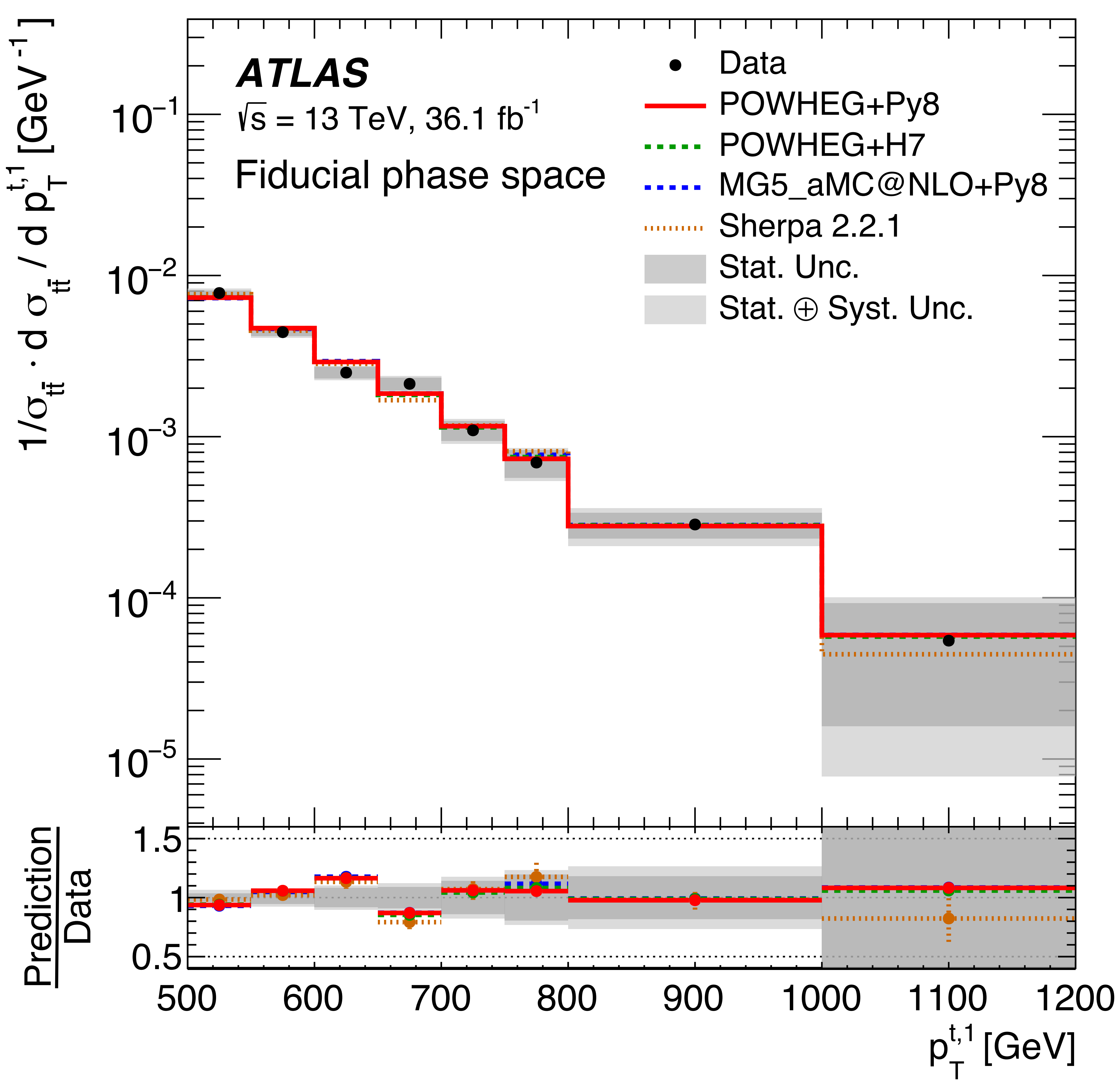
tt all-hadronic differential cross sections — event selection

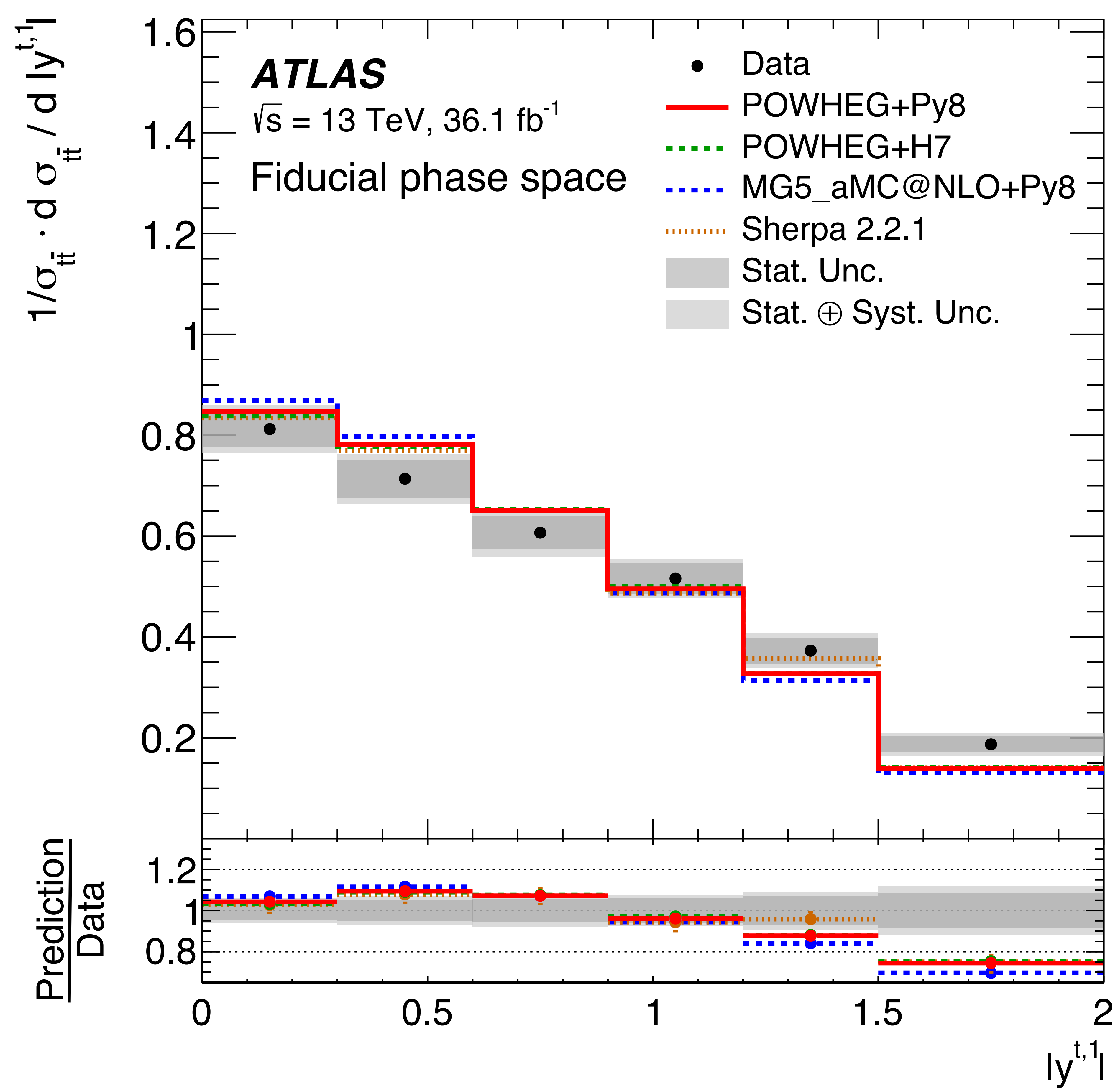


- Multijet background suppressed by top tagging algorithm: uses jet mass and τ_{32} (prefers 3-pronged jets) (Link to top tagging note) — See Emma's talk!
- Both large-*R* jets contain an associated small-*R* b-tagged jet
- Remaining background estimated using ABCD method with 16 regions

tt all-hadronic differential cross sections — results

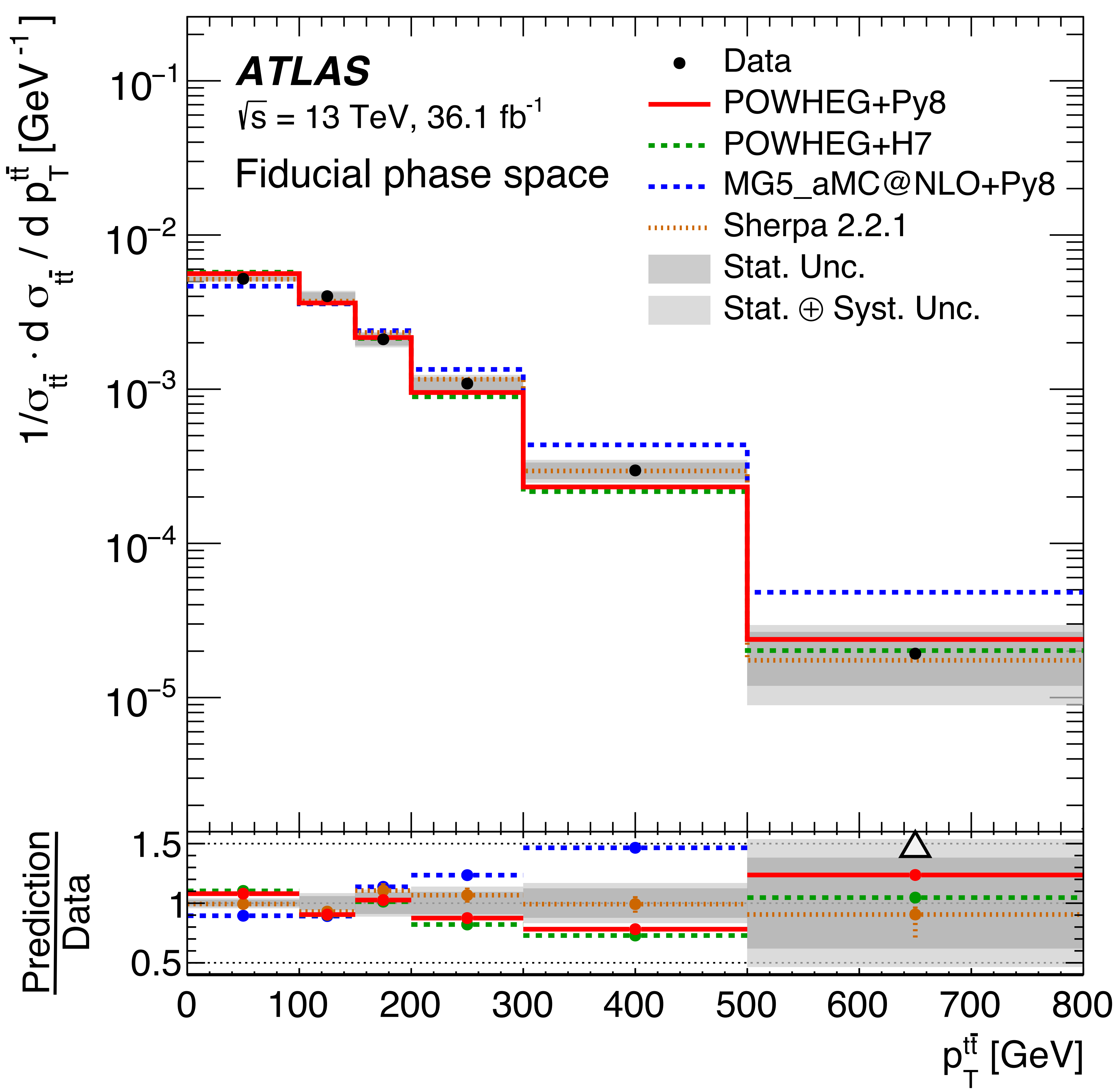
- Link to paper: arXiv:1801.02052
- Particle level leading top p_T and |rapidity|

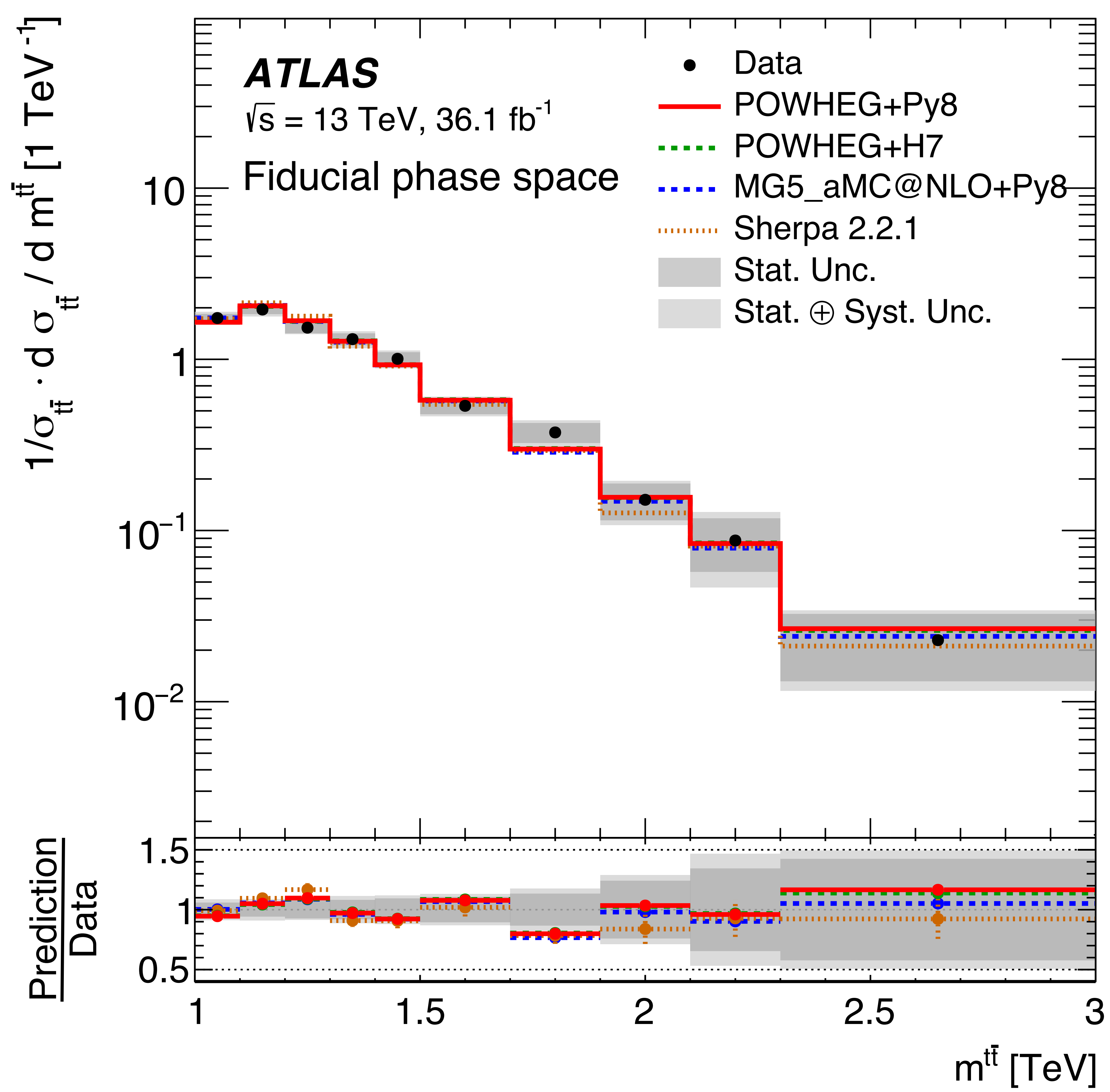




tt all-hadronic differential cross sections — results

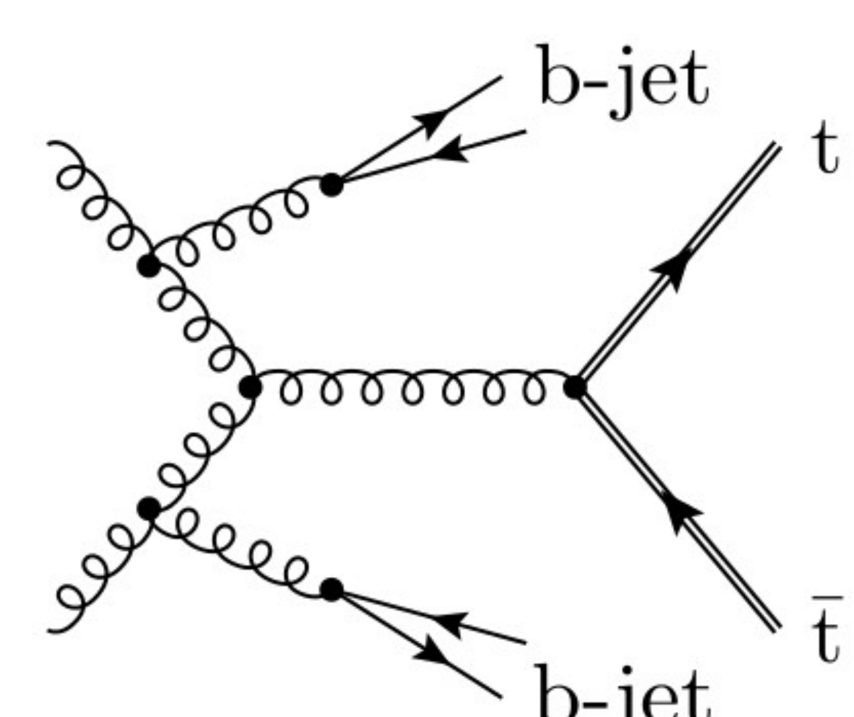
- Link to paper: arXiv:1801.02052
- Particle level tt system p_T and invariant mass

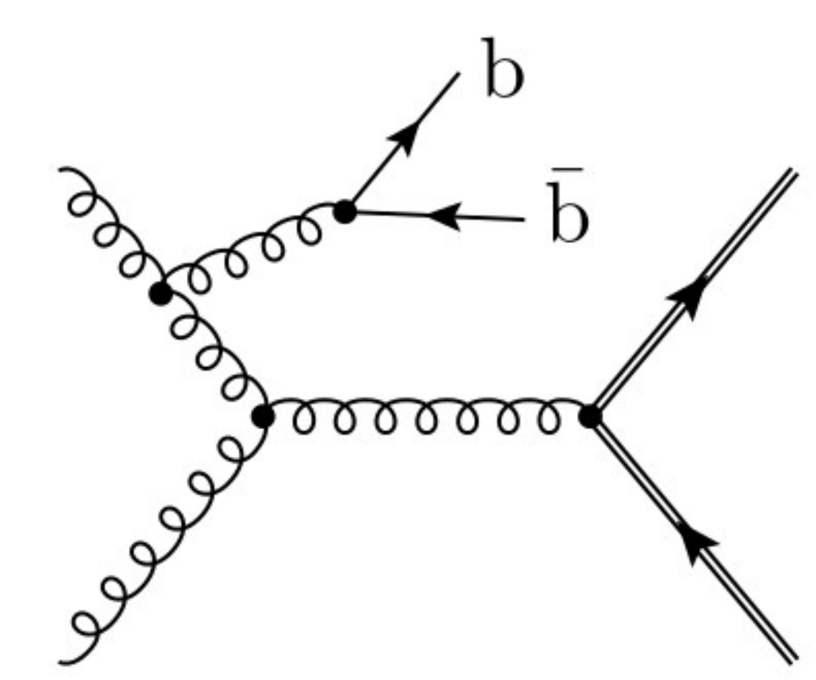




tt+bb — strategy

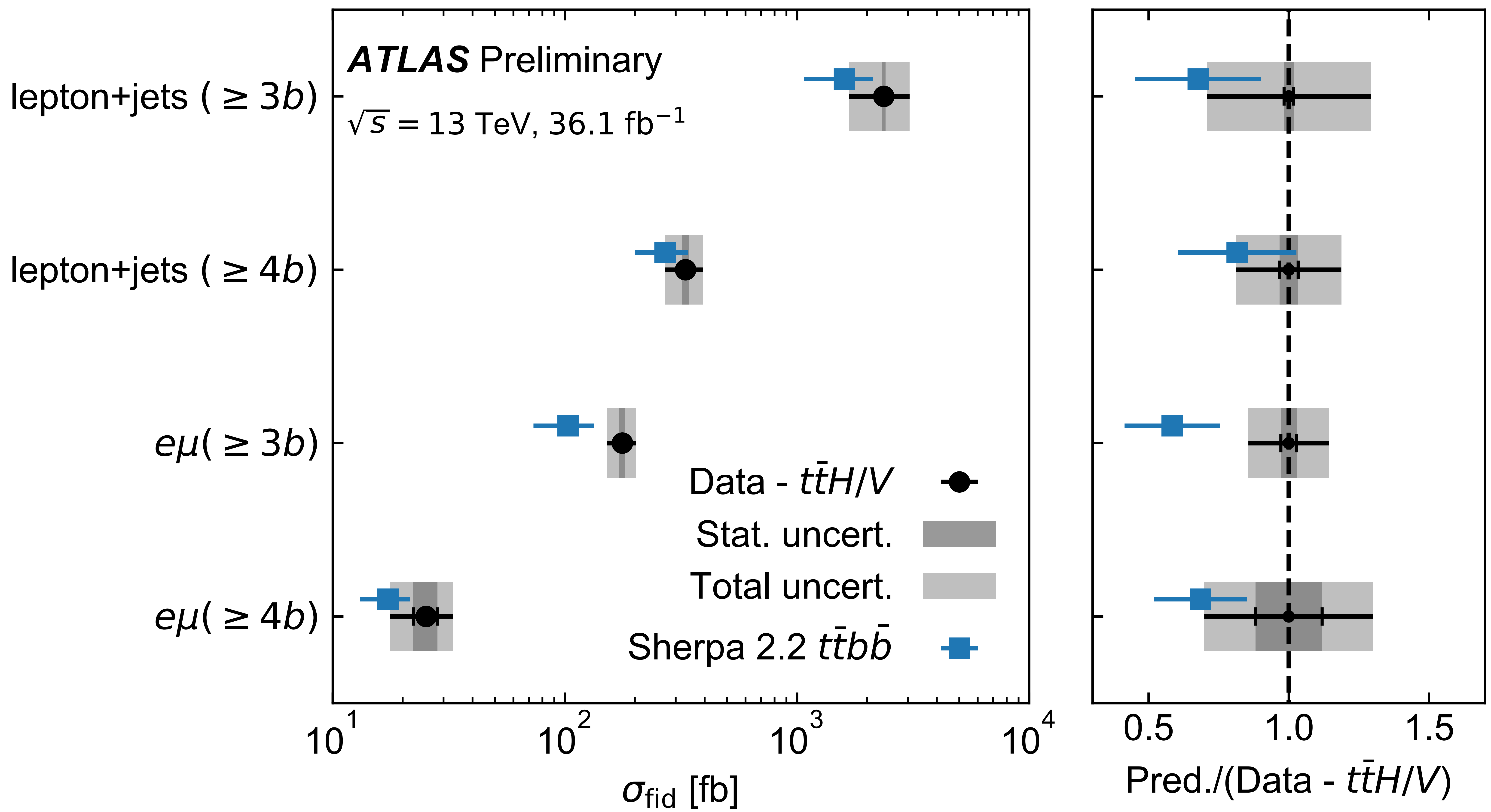
- tt + b-jets challenges QCD calculations with the heavy b quark
- tt+bb is a large background (and dominant systematic) for ttH(H→bb). Only modelled to NLO by generators. Let’s measure it.
- Link to note, 36.1 fb^{-1} @ 13 TeV, dilepton/l+jets channels
- Data-driven template fit to derive correction factors for flavour composition for tt+X
- Result: differential cross sections as functions of kinematic variables of b-jet pairs
  - Min ΔR(b,b): expected to be from gluon splitting
  - Highest p_T: dominated by top pair production





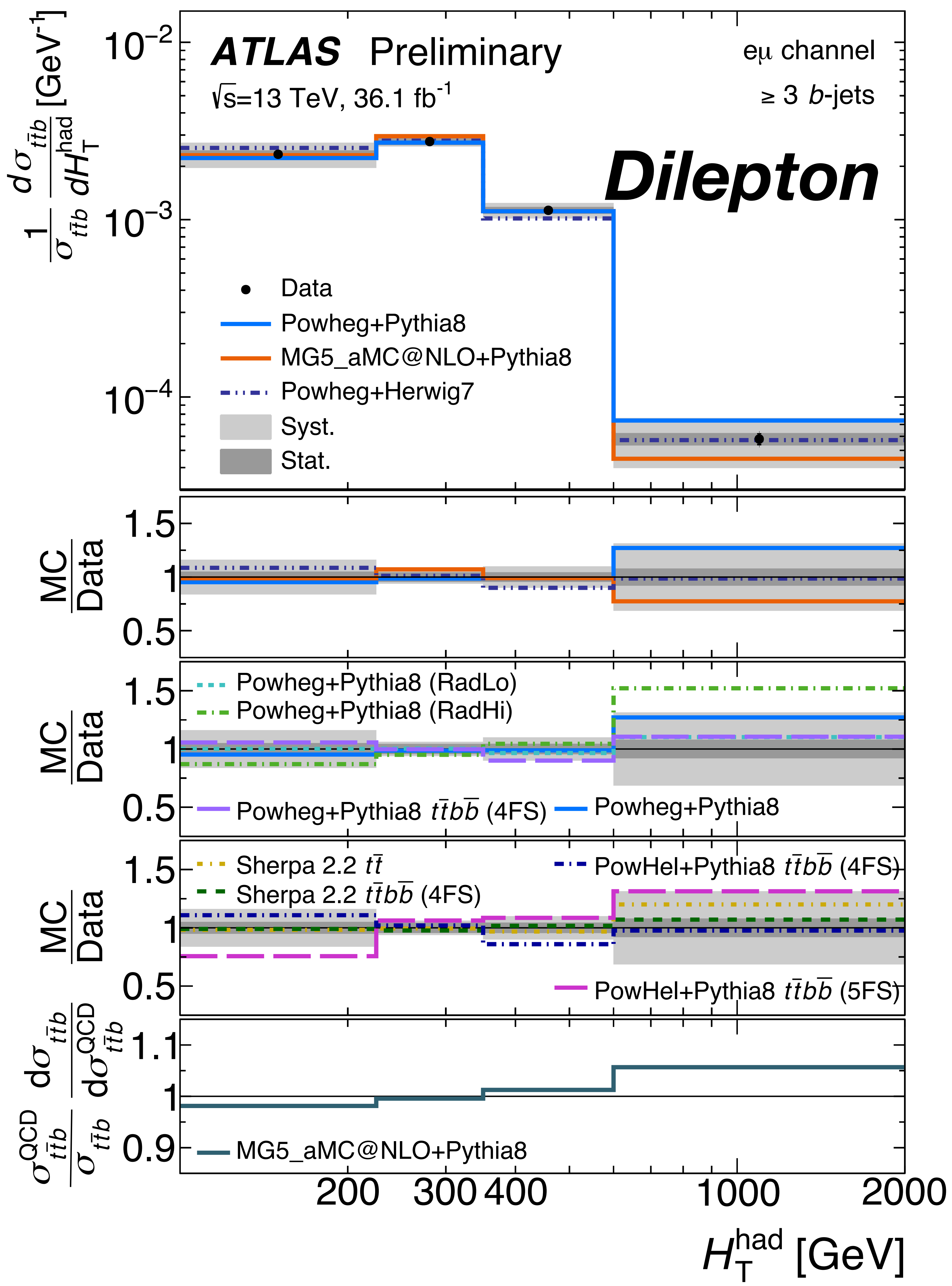
tt+bb — inclusive fiducial cross section results

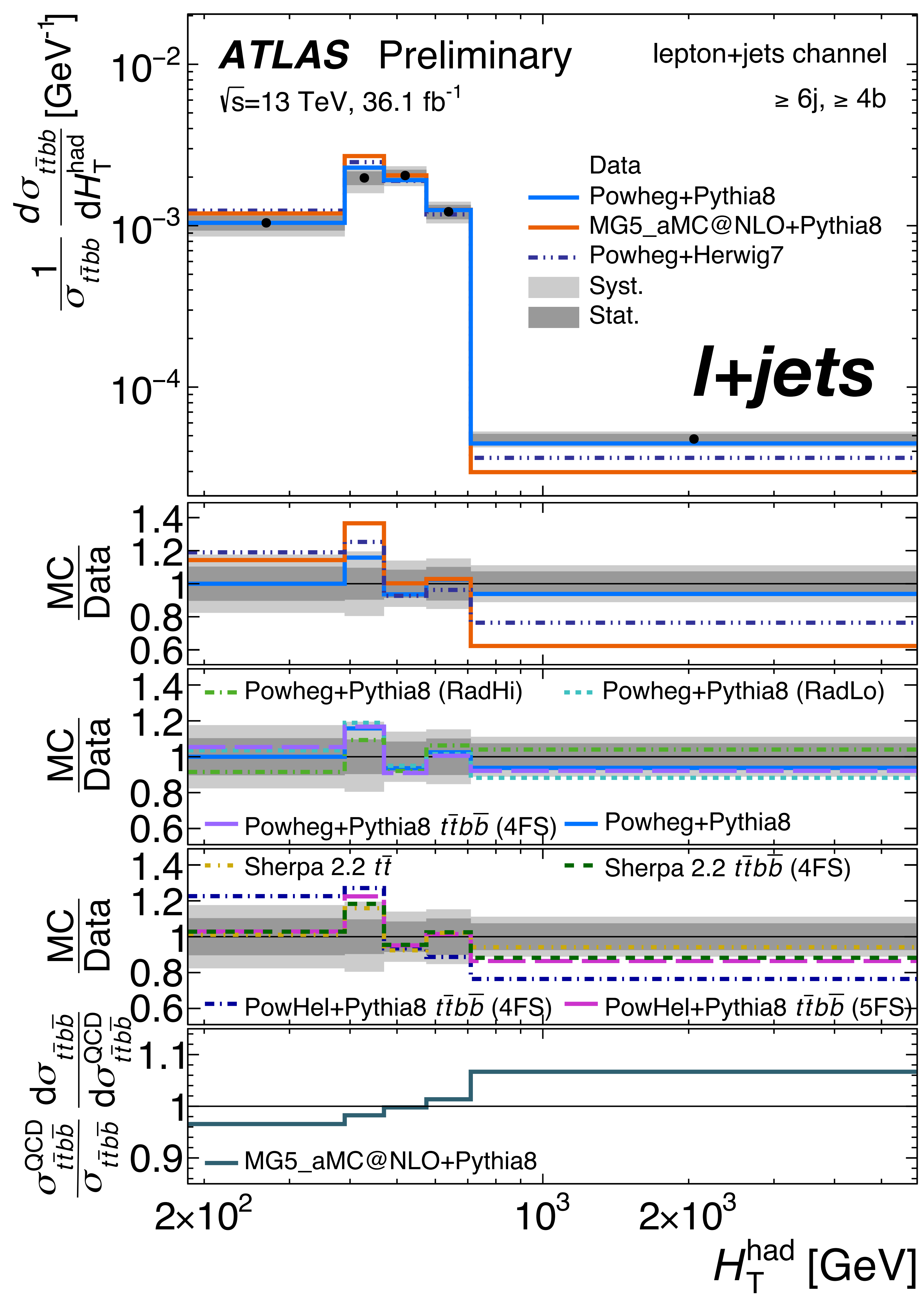
- Generally exceed NLO predictions, but compatible within uncertainties

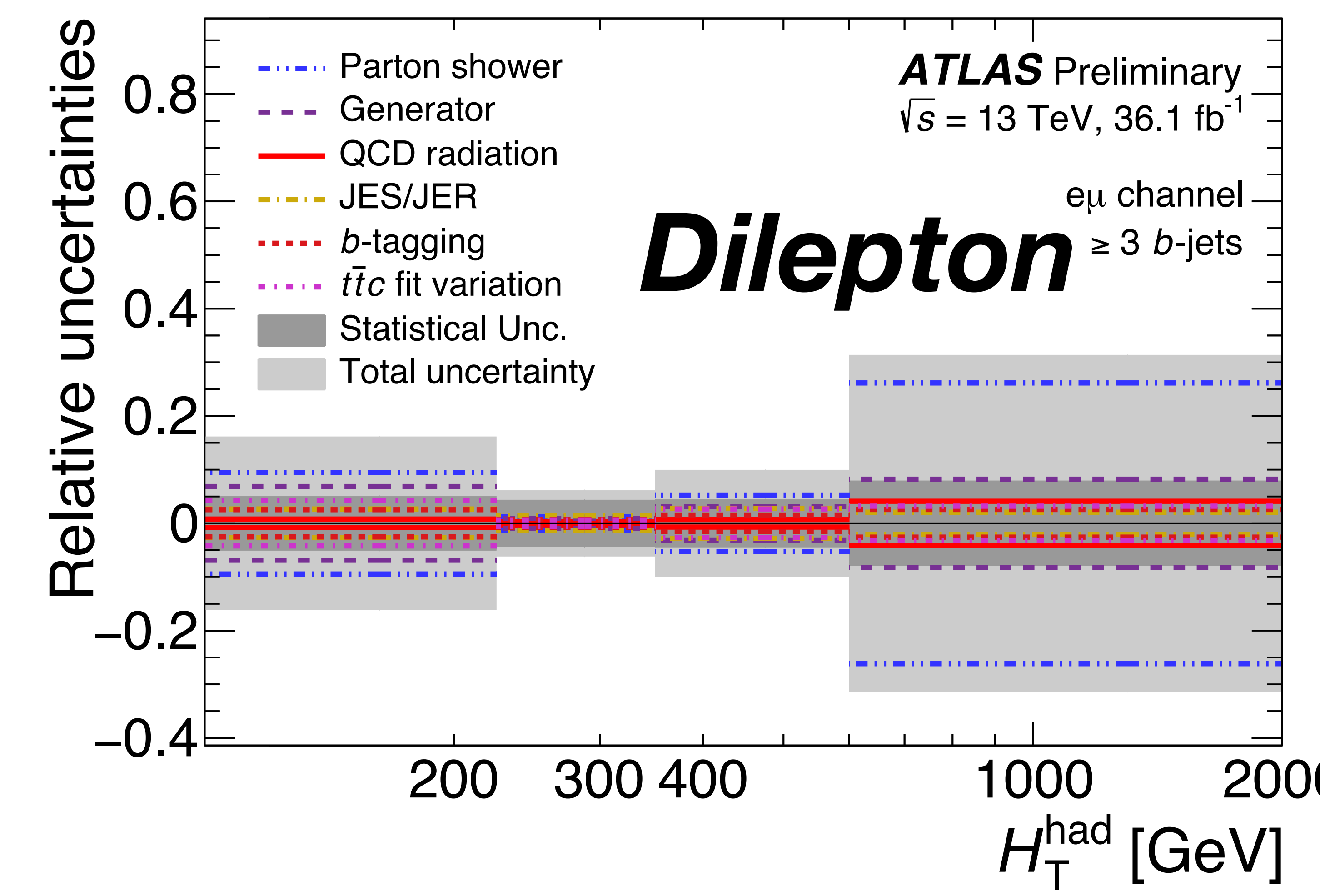


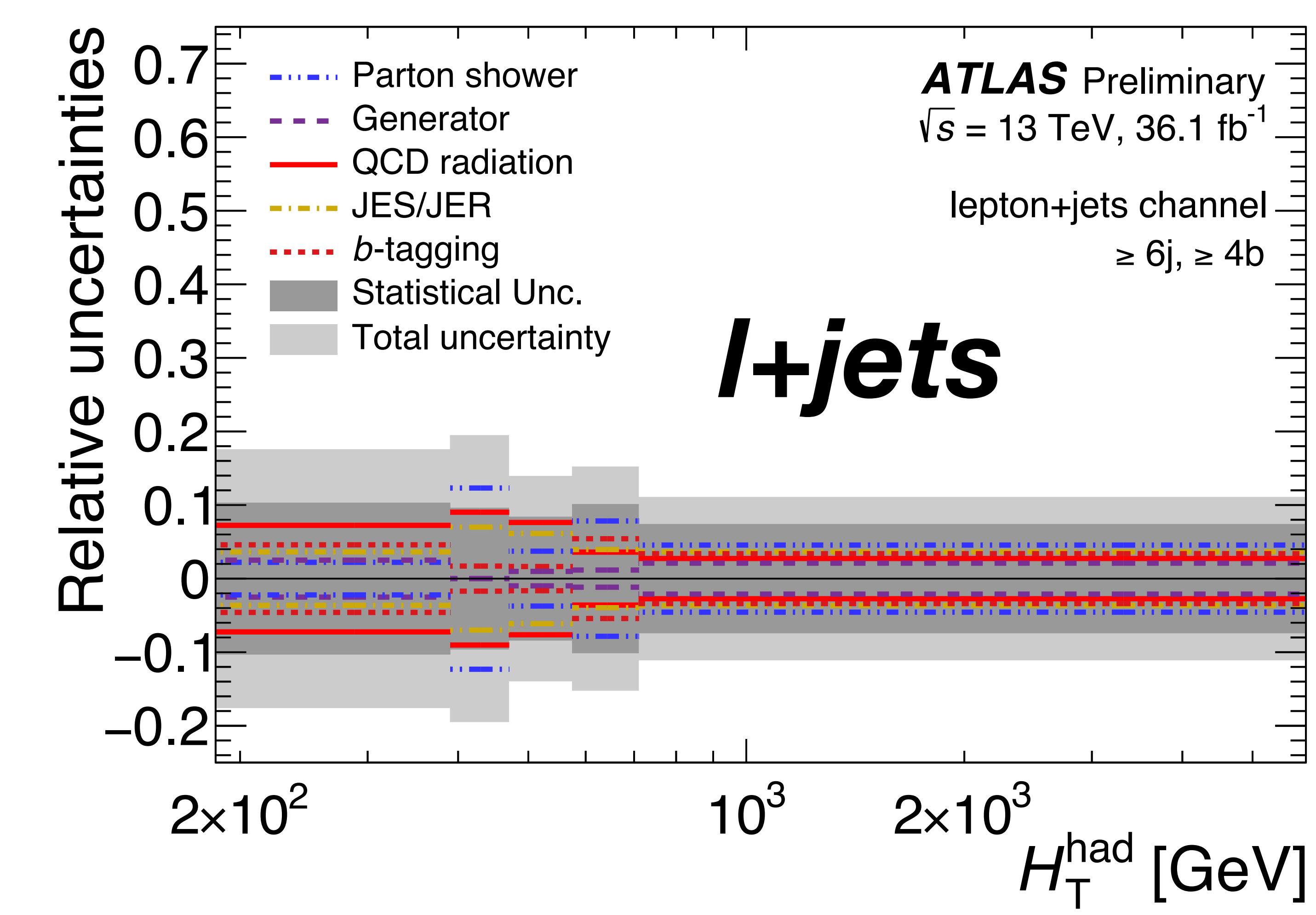
tt+bb — differential cross section results

- Systematic modelling uncertainties dominate the experimental ones





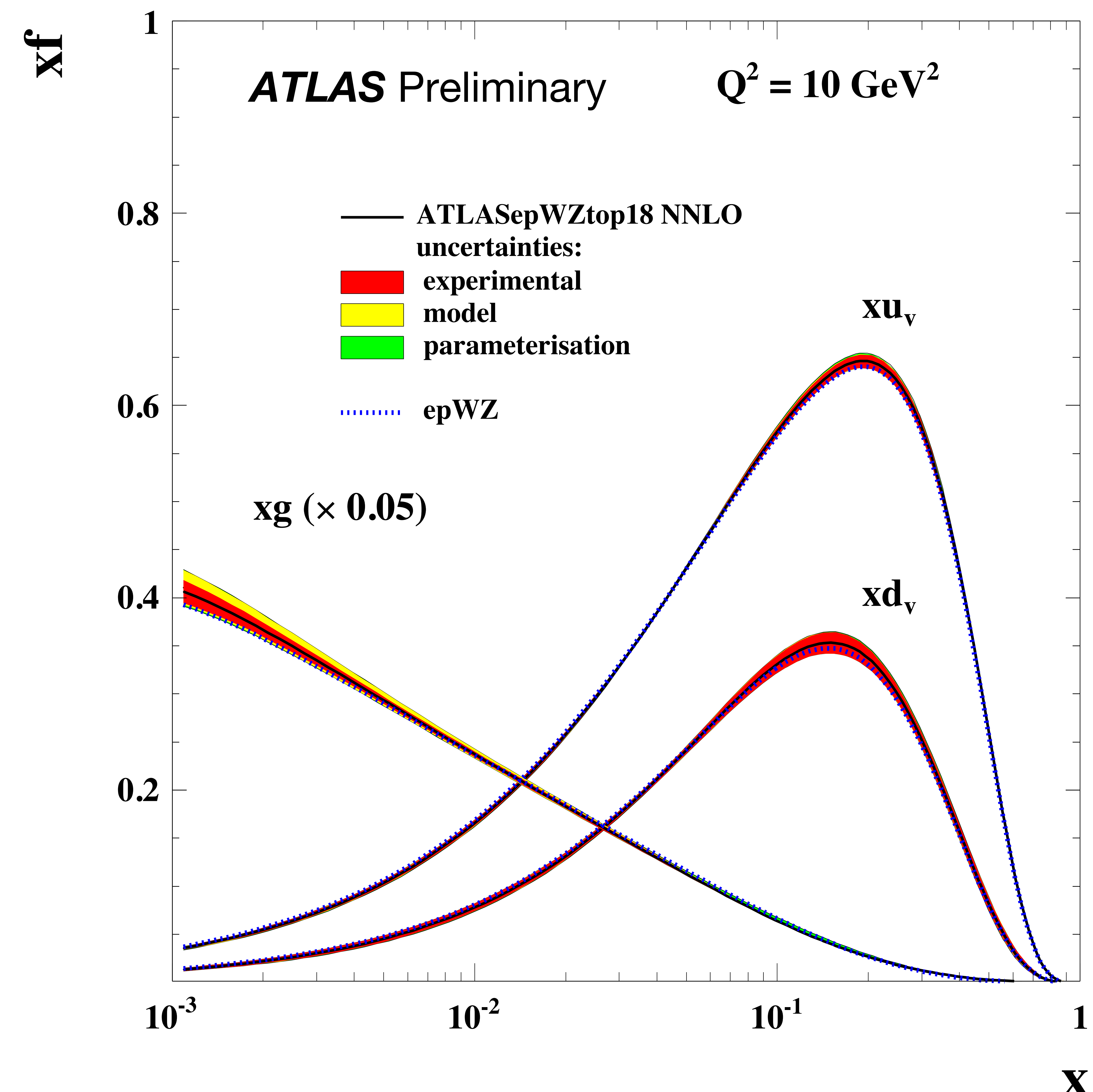




PDF fits

- Goal: fit ATLAS W, Z/γ^* cross sections (7 TeV), **tt p_T+m_{tt}+y_{tt}** distributions (8 TeV), HERA $e^{\pm}p$ DIS data to produce new PDF set ATLASepWZtop18
- Use full correlation information to perform simultaneous fit — increases impact of tt data
- After including tt data gluon PDF is slightly harder, lower uncertainty at high x

Link to note



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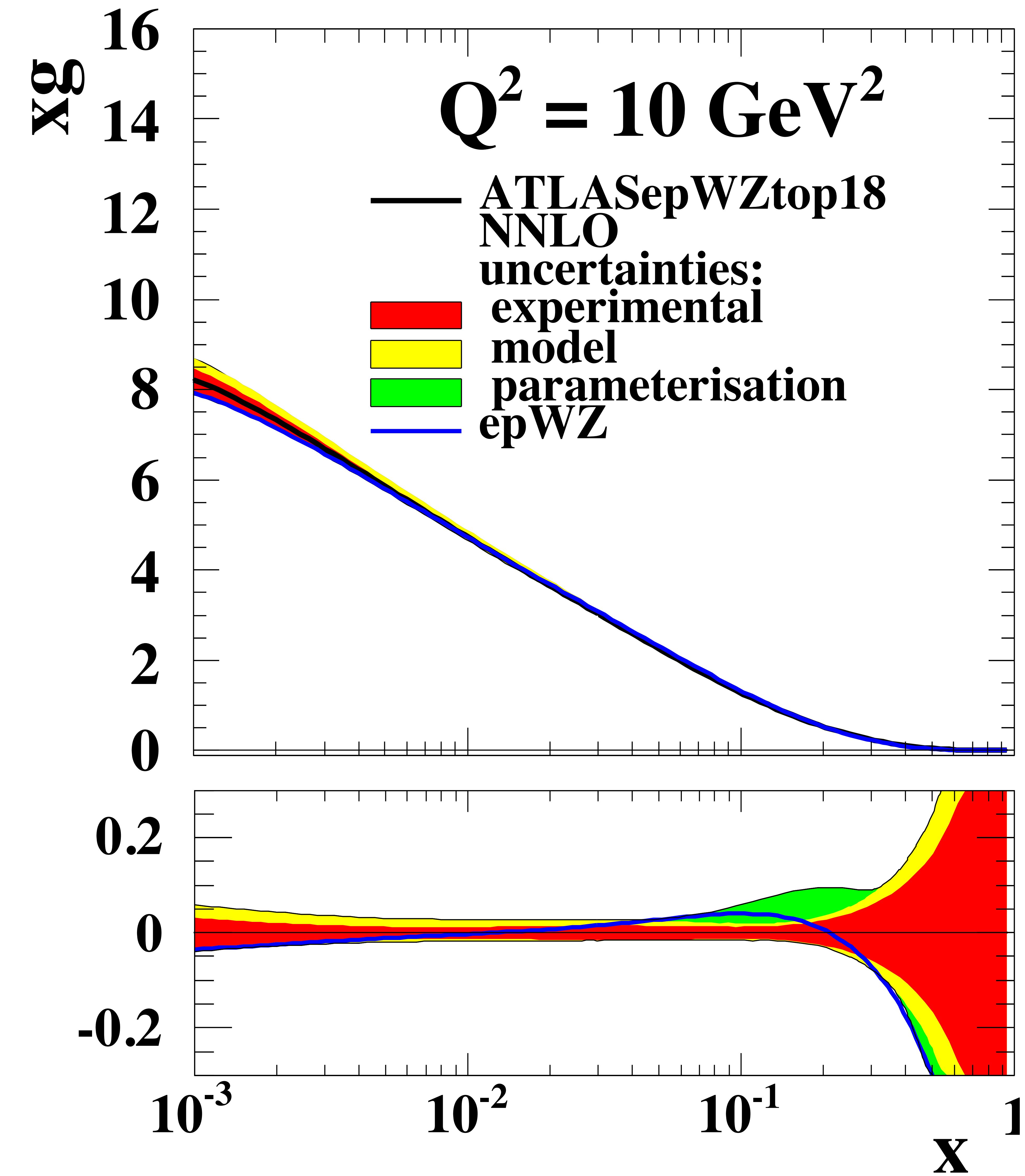

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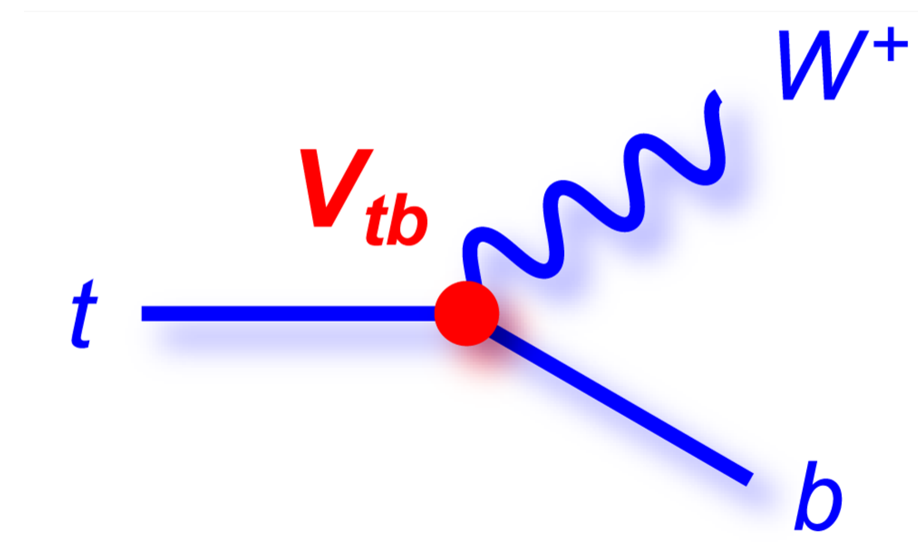
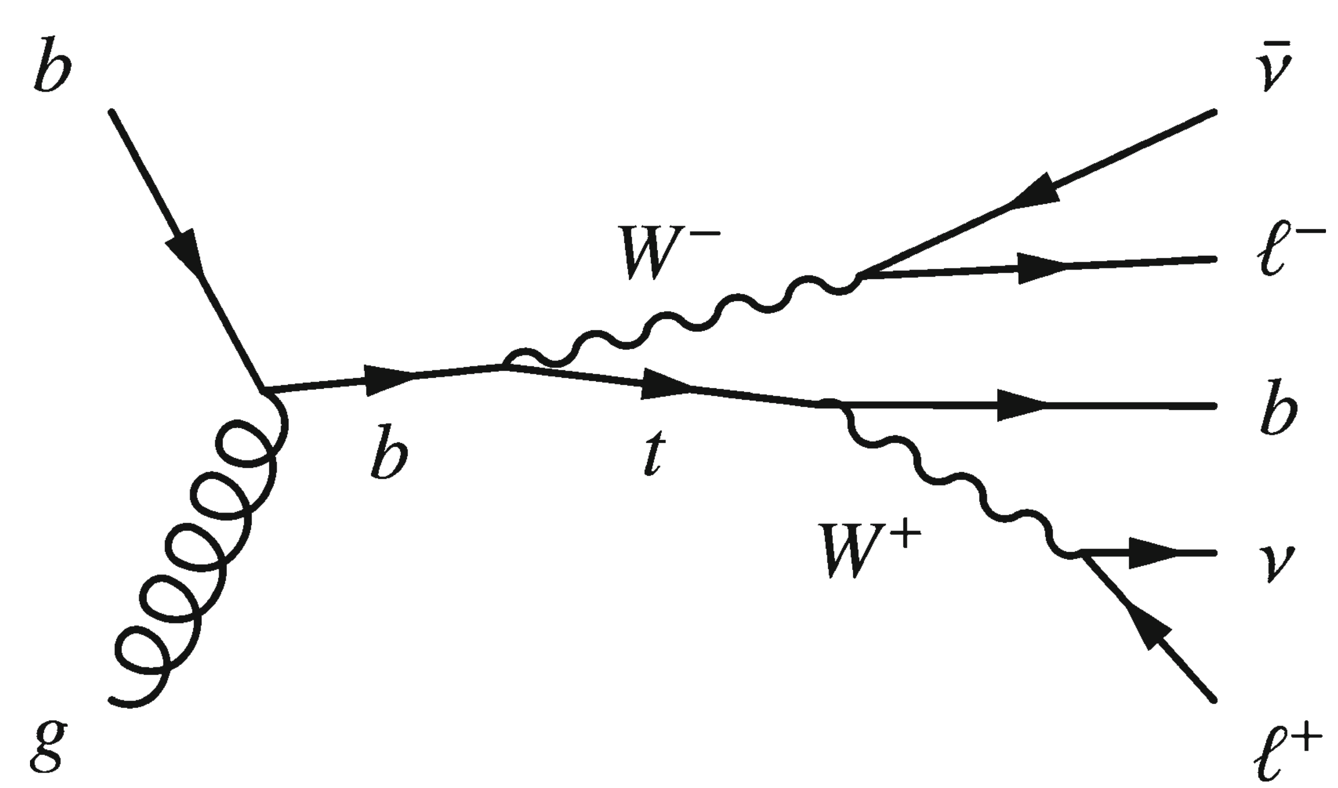
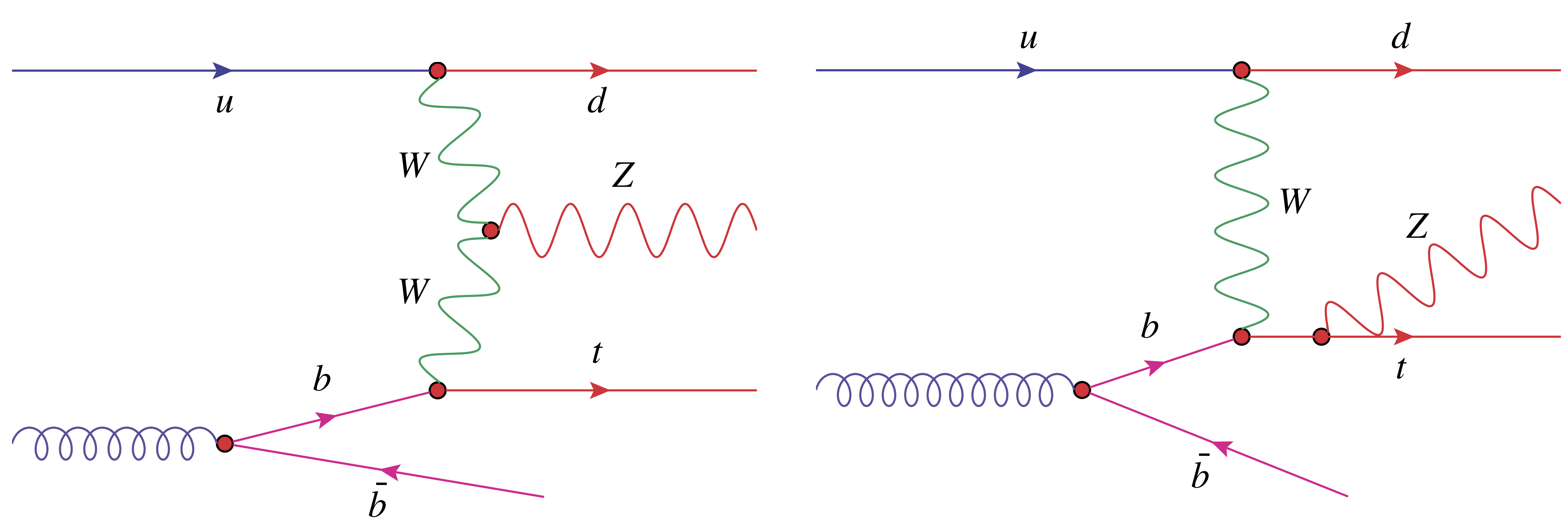
Single top — motivation

- Direct determination of *tWb* vertex
- Measurement of CKM matrix element magnitude $|V_{\mathrm{tb}}|$
- *tWb* anomalous couplings — sensitive to BSM physics
- Single top interferes with tt at higher orders of α_s



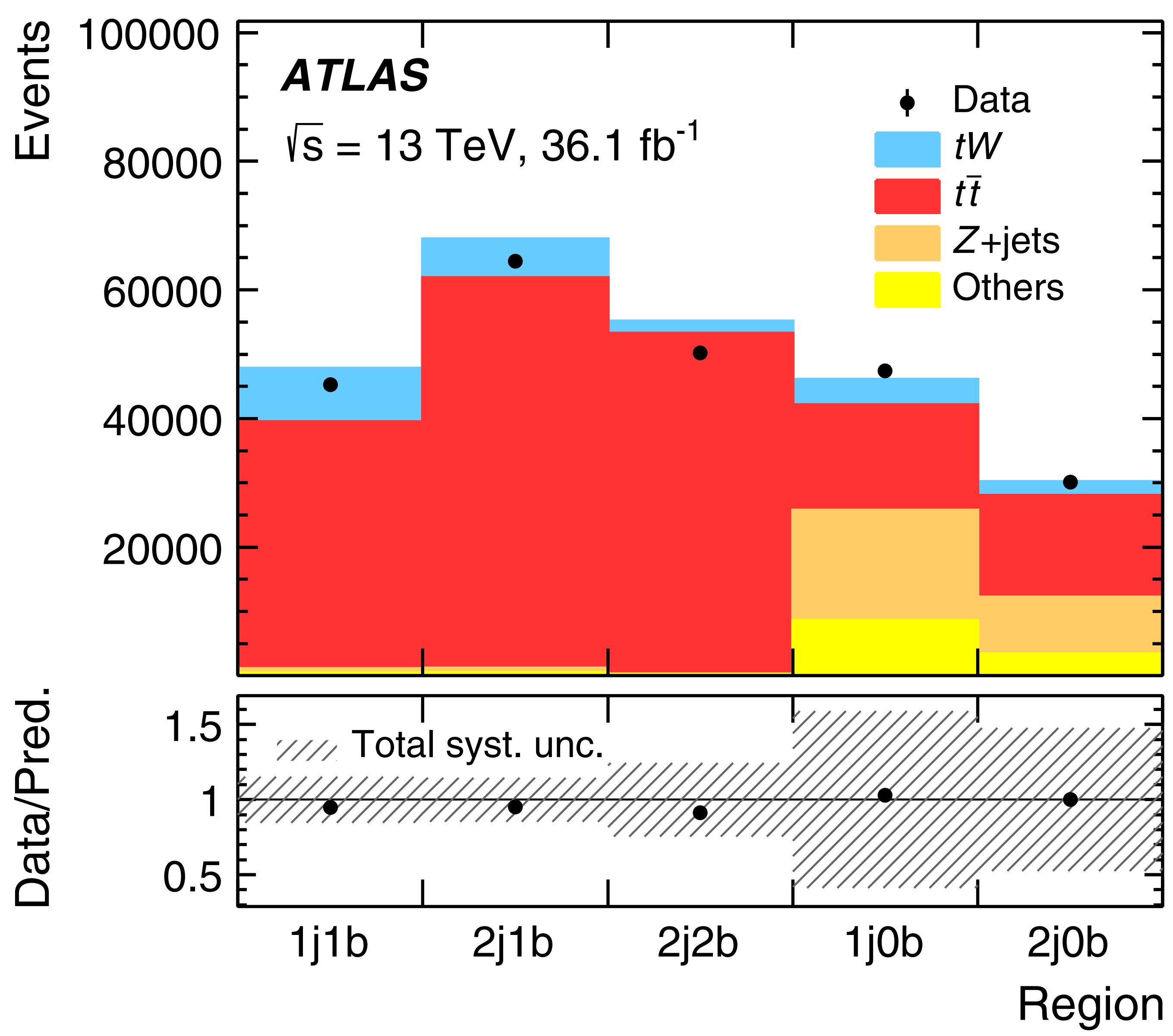


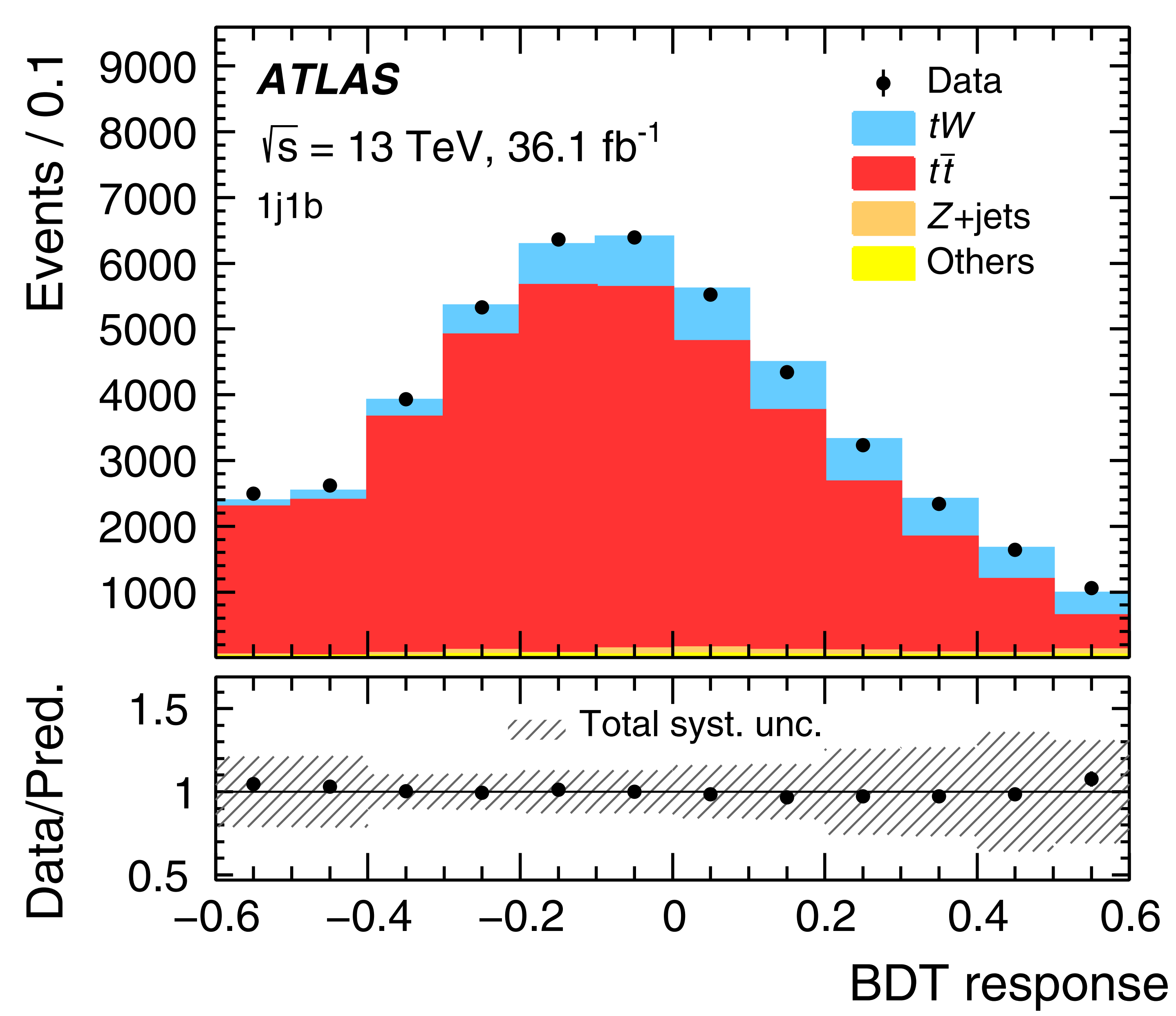


(a) (b)

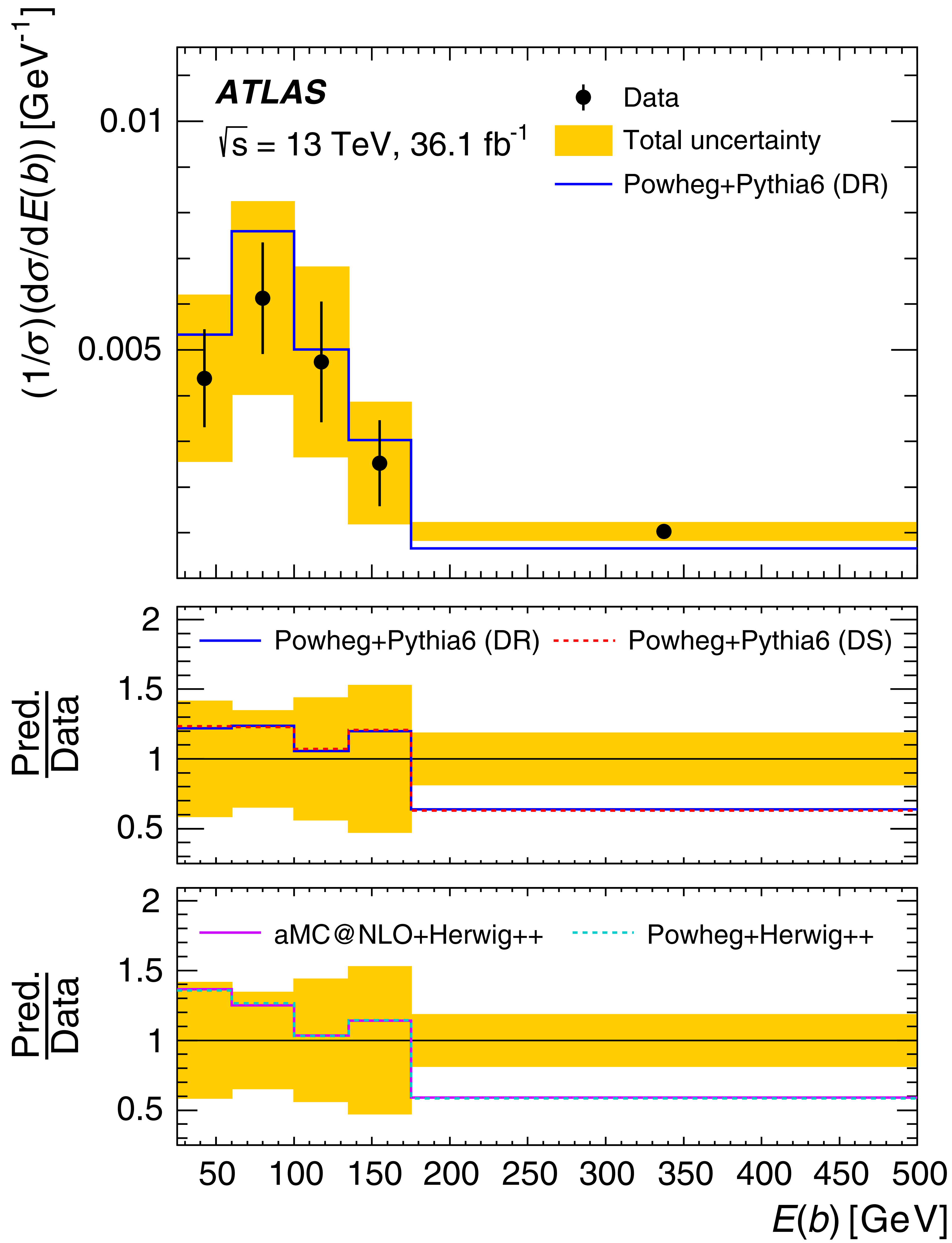
tW — strategy

- First tW differential cross section, 36.1 fb^{-1} @ 13 TeV, Link to paper
- Dileptonic final state containing 1 b-tagged jet and 2 neutrinos
- Signal region: 2 leptons, exactly 1 b-jet
  - Not considering >1 b-jets supresses tt background and tt/tW interference
  - BDT separates tW signal from large tt background
  - Events vetoed if dilepton invariant mass is inside a Z window
- Unfolded to fiducial phase space

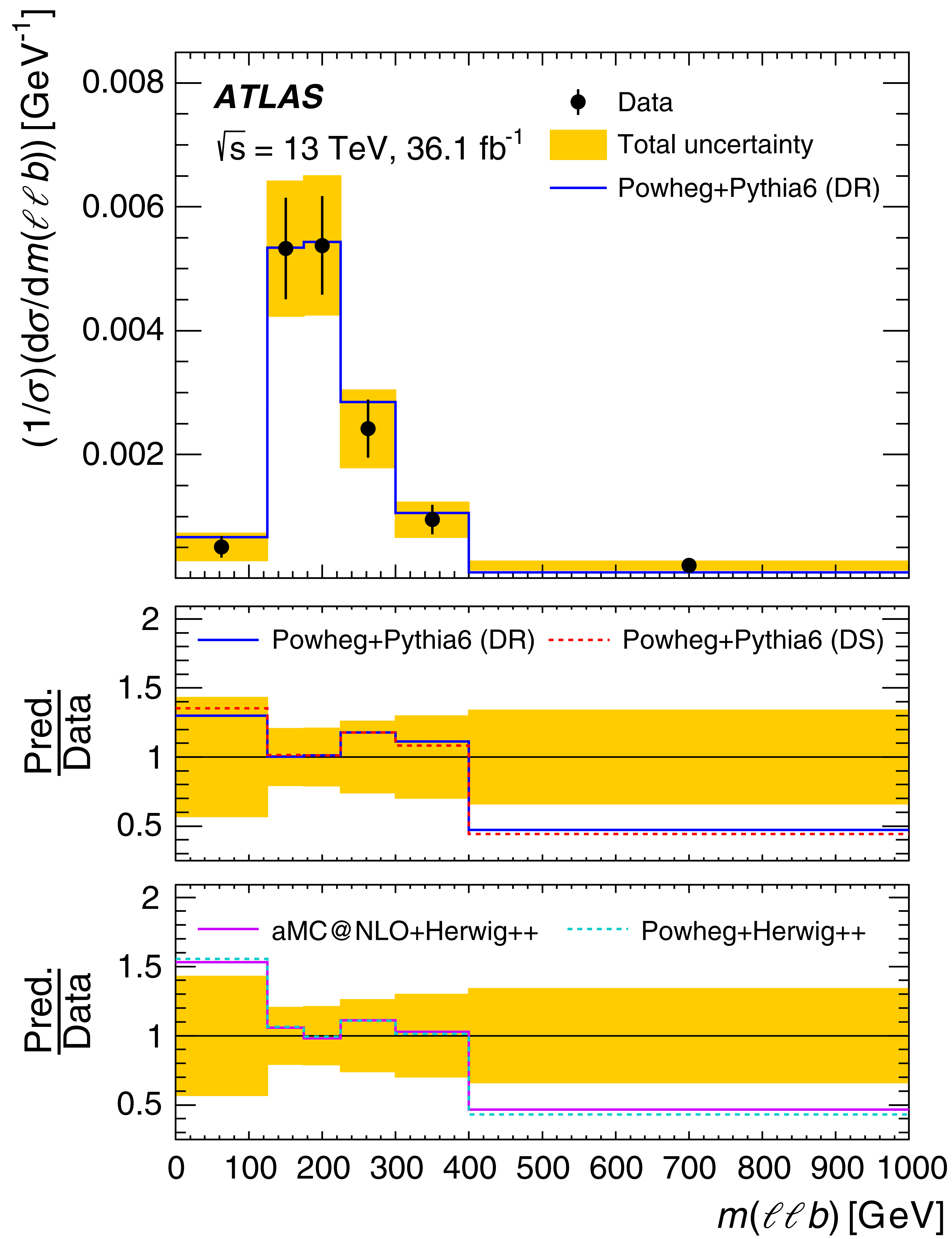




tW — results



ATLAS
√s = 13 TeV, 36.1 fb-1
Data
Total uncertainty
Powheg+Pythia6 (DR)
Powheg+Pythia6 (DS)
aMC@NLO+Herwig++
Powheg+Herwig++
(1/σ)(dσ/dE(b)) [GeV-1]
Pred./Data
E(b) [GeV]



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√s = 13 TeV, 36.1 fb-1
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Total uncertainty
Powheg+Pythia6 (DR)
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Powheg+Herwig++
(1/σ)(dσ/dm(ℓℓb)) [GeV-1]
Pred./Data
m(ℓℓb) [GeV]

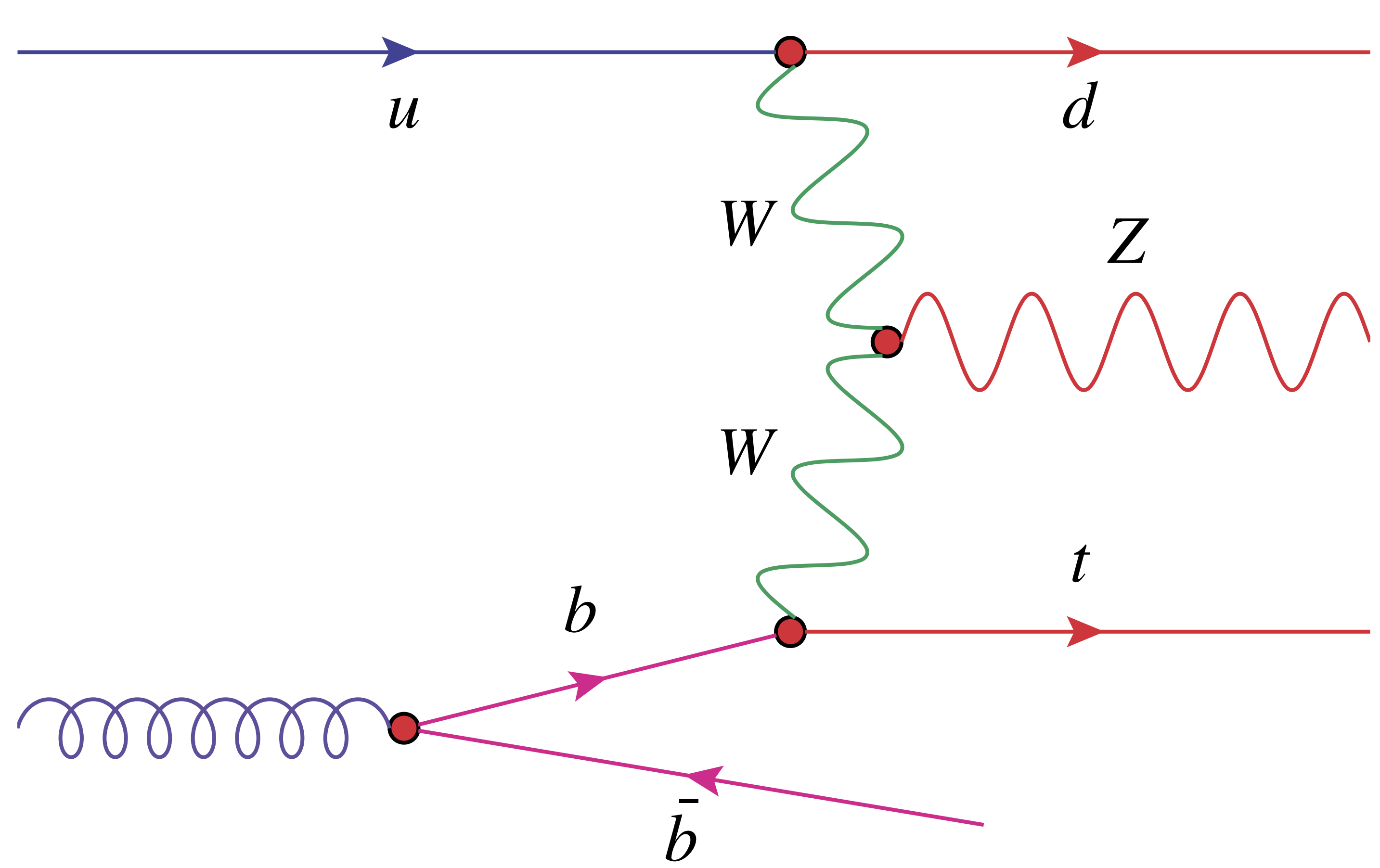
tZ — strategy

- 36.1 fb^{-1} @ 13 TeV, Link to paper
- Inclusive cross section measurement
- tZq final state with 3 leptons + 2 jets (1 b-tag)
- Backgrounds: WZ/ZZ, tt, Z+jets
- Neural network discriminant

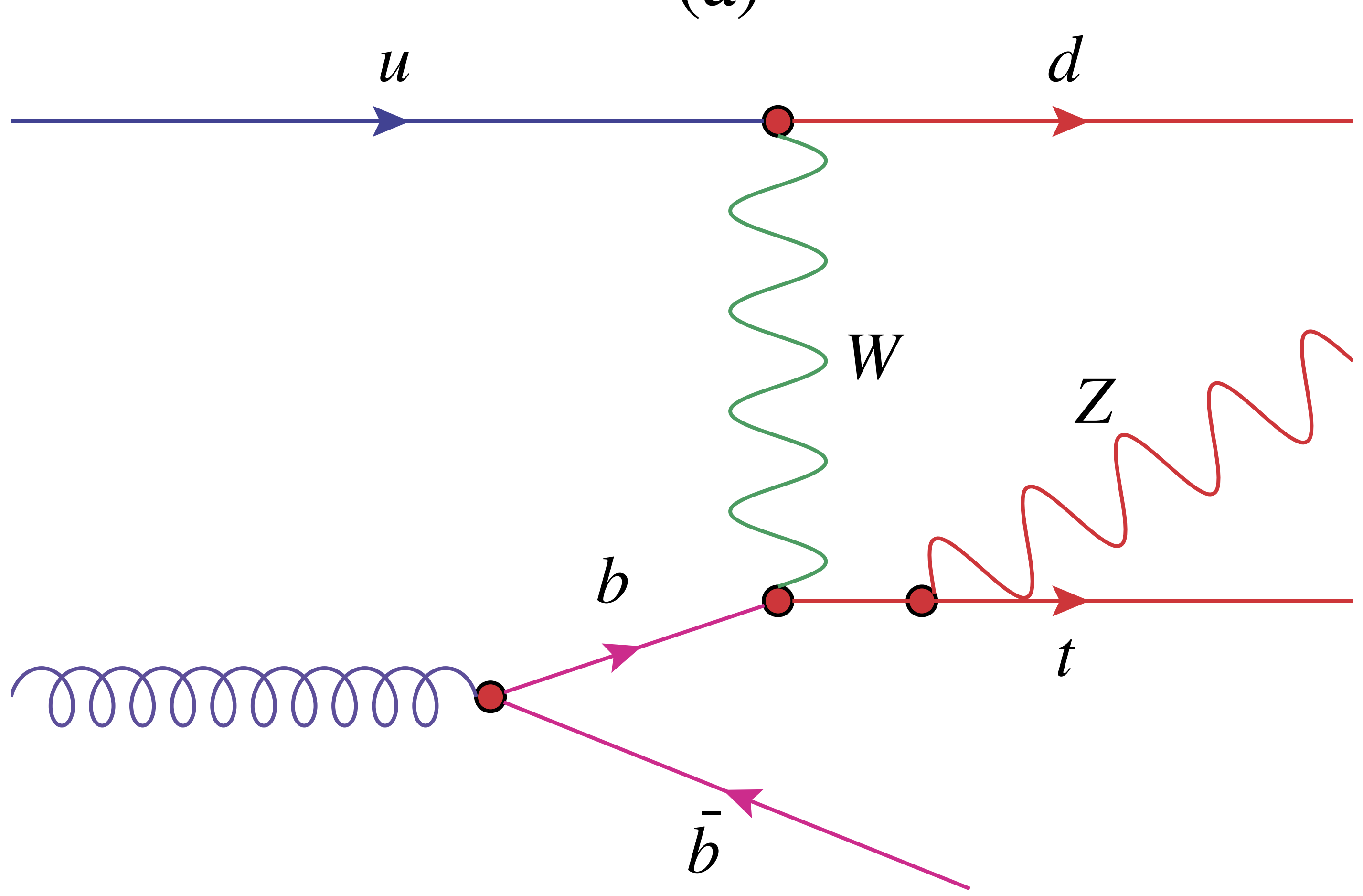
Variables used as input to the neural network, ordered by their separation power.

Variable	Definition
$\lvert\eta(\mathrm{j})\rvert$	Absolute value of untagged jet η
$p_\mathrm{T}(\mathrm{j})$	Untagged jet p_T
m_t	Reconstructed top-quark mass
$p_\mathrm{T}(\ell^W)$	p_T of the lepton from the W-boson decay
$\Delta R(\mathrm{j}, Z)$	ΔR between the untagged jet and the Z boson
$m_\mathrm{T}(\ell, E_\mathrm{T}^\mathrm{miss})$	Transverse mass of W boson
$p_\mathrm{T}(t)$	Reconstructed top-quark p_T
$p_\mathrm{T}(b)$	Tagged jet p_T
$p_\mathrm{T}(Z)$	p_T of the reconstructed Z boson
$\lvert\eta(\ell^W)\rvert$	Absolute value of η of the lepton coming from the W-boson decay

Lowest-order tZq diagrams
In four-flavour scheme



(a)

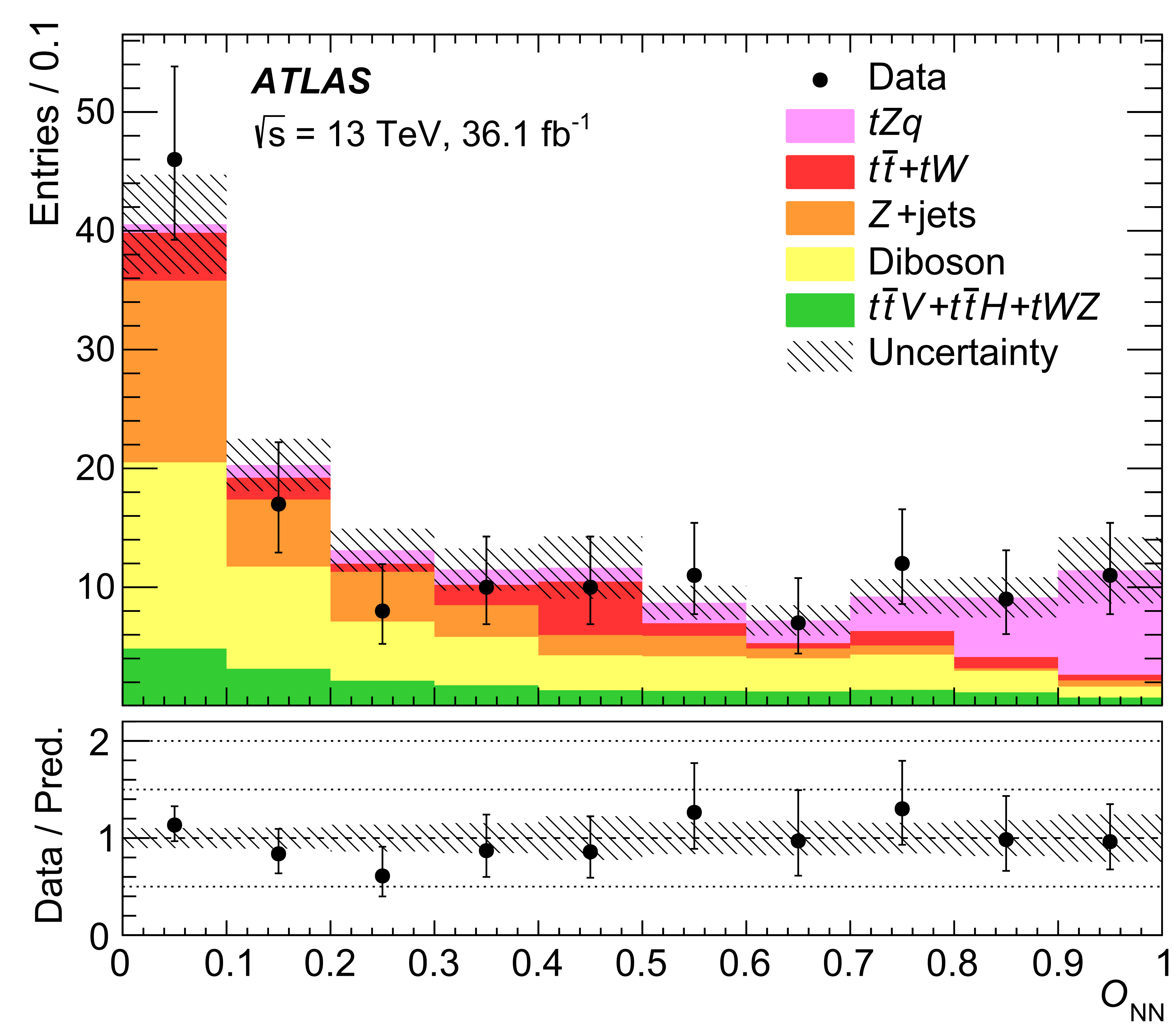


(b)

tZ — results

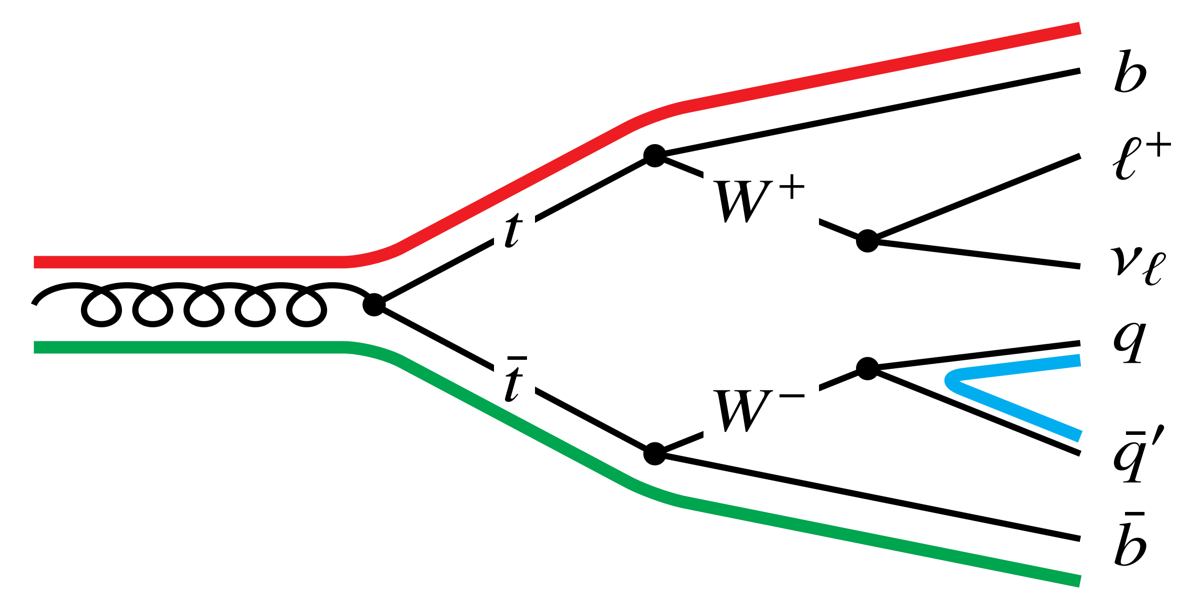
- Binned Poisson likelihood maximised to fit signal strength μ
- $\mu = 0.75 \pm 0.21\ (stat.) \pm 0.17\ (syst.) \pm 0.05\ (th.)$
- Profile likelihood ratio defines test statistic q_μ
- $p_0 = 1.3 \times 10^{-5}$
- Observed (expected) significance: 4.2σ (5.4σ)

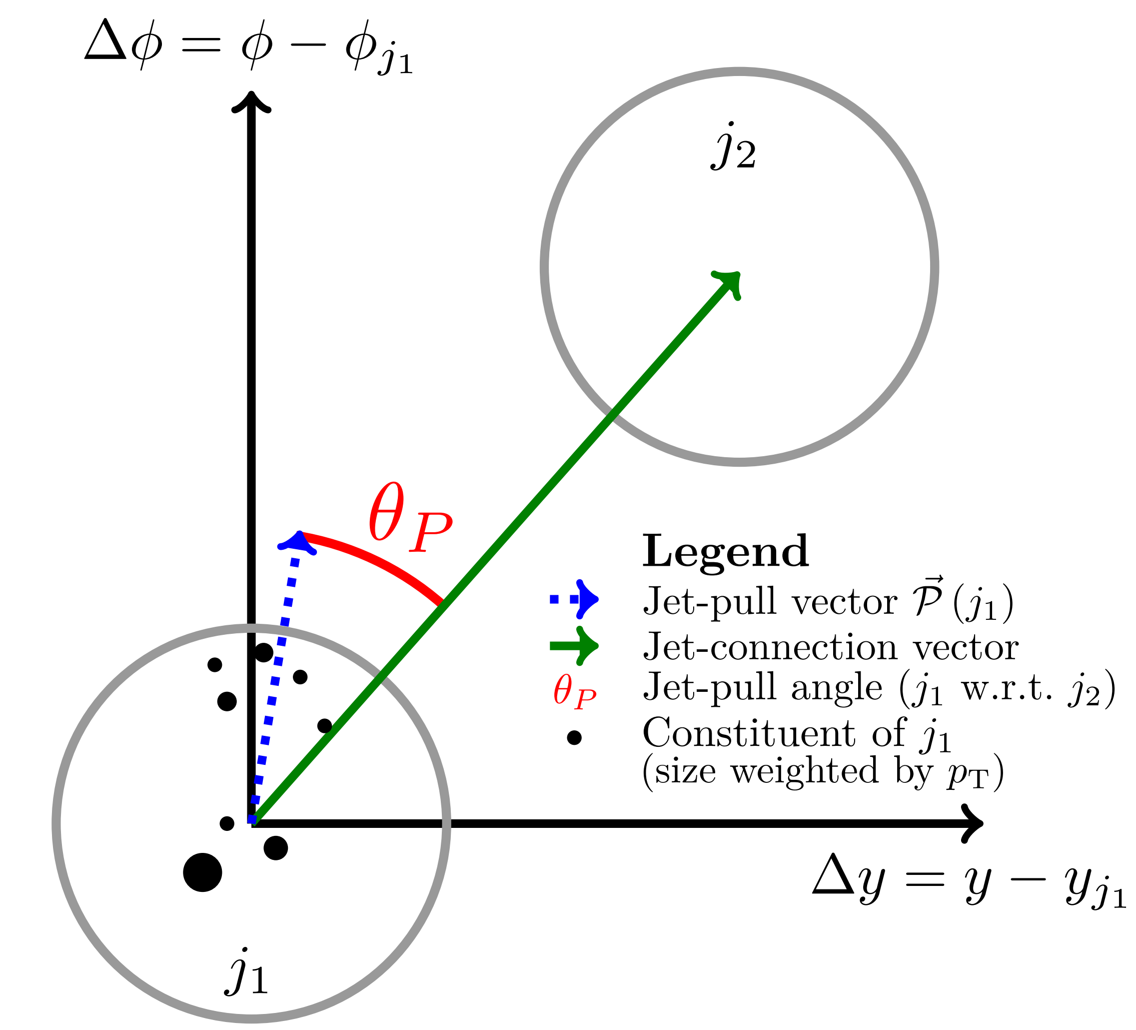
Post-fit neural network output



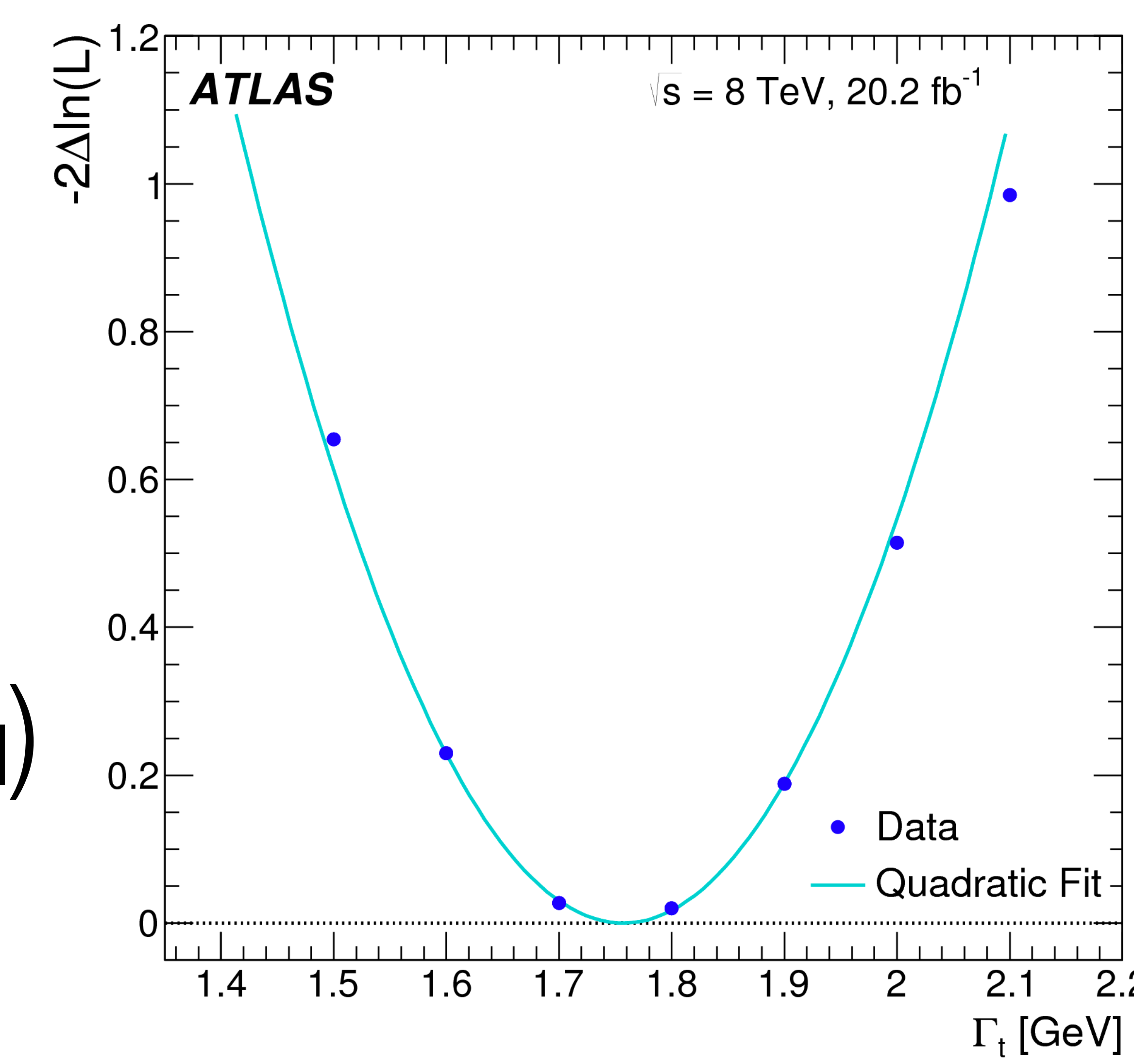
Top quark properties

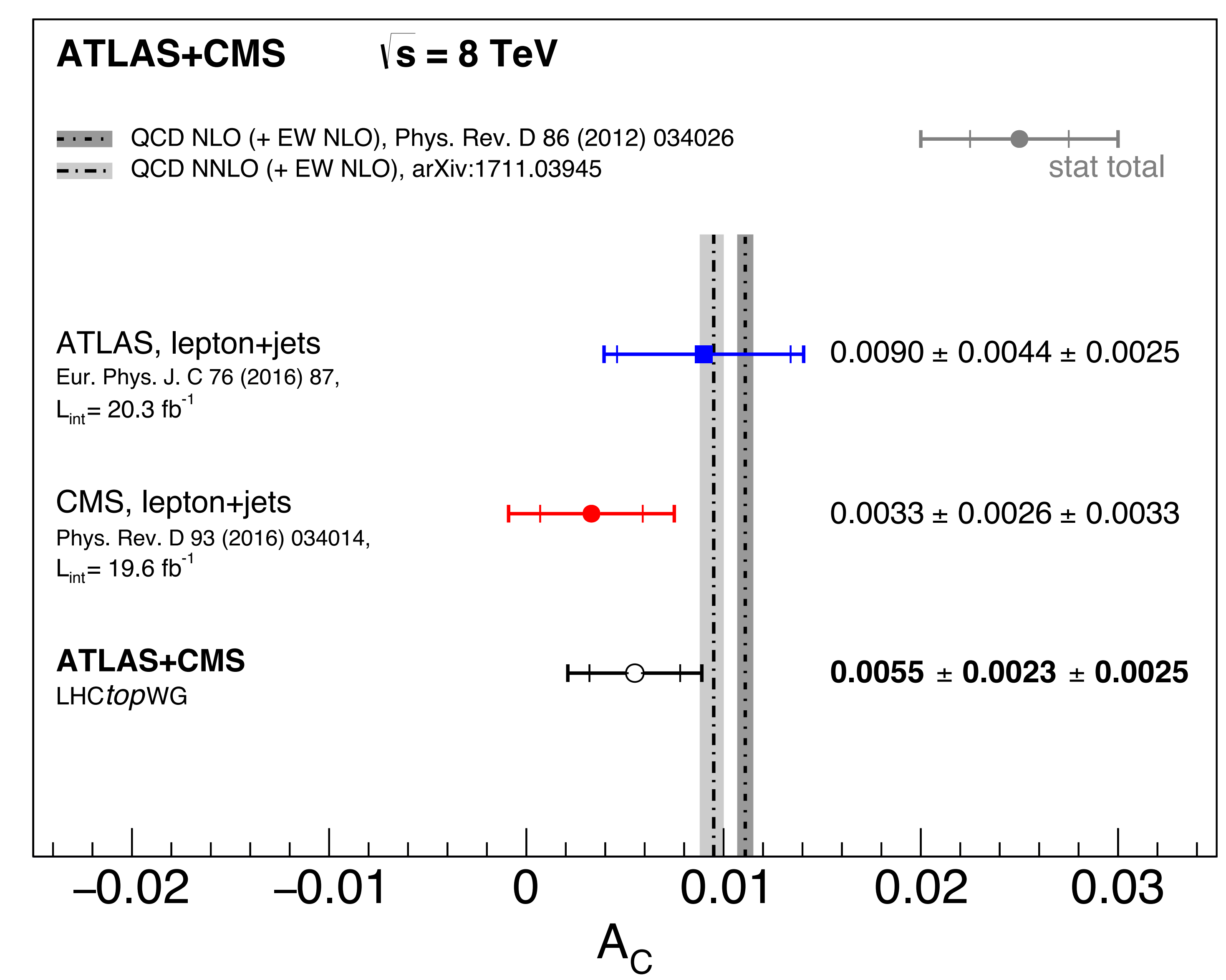
- Colour flow: link





- Charge asymmetry: link
  - Combination of ATLAS and CMS reults from 7 and 8 TeV
  - Result consistent with SM (no charge asymmetry)
- Width: link
  - 20.2 fb^{-1} @ 8 TeV
  - Template fit m_{lb} and $\Delta R_{min}(j_b, j_l)$

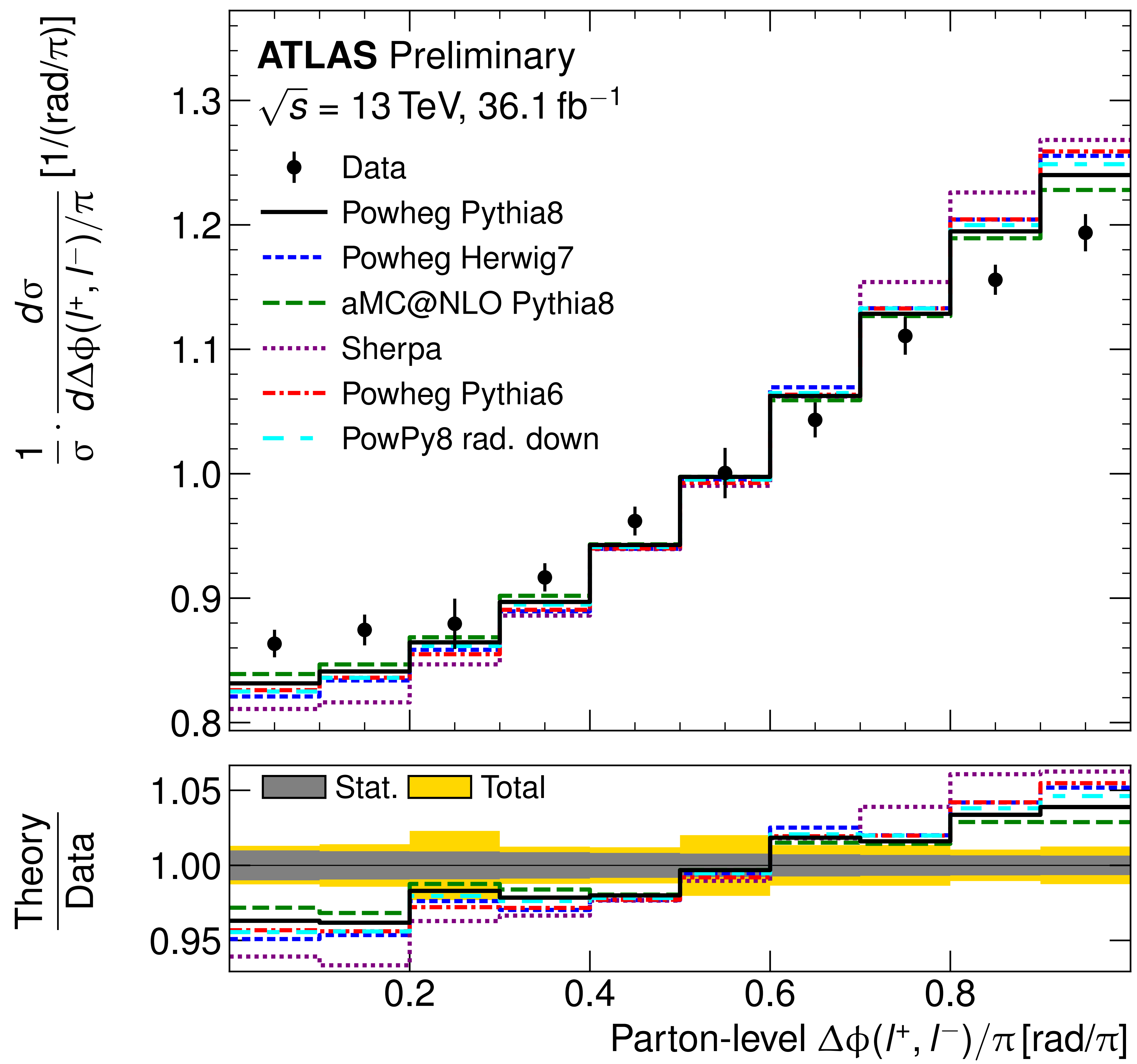




Spin correlation — strategy

- The SM predicts top quark and anti-quark spins to be correlated in tt pairs
- Spin information is carried by the top quark decay products, particularly accessible in charged leptons
- Measure unfolded $|\Delta\phi|$ differential cross section in dileptonic channel
- Sensitive to BSM physics: SUSY stops, used for EFT fits (chromo-EM)
- tt system reconstructed using neutrino weighting method: assumes on-shell tops and W bosons to solve for neutrino 4-momenta

Spin correlation — results



- Link to note
- Maximum-likelihood fit to determine f_{SM}

$$n_i = f_{SM}\, n_{spin} + (1 - f_{SM})\, n_{no\ spin}$$

Region	f_{SM}	Significance (incl. theory uncertainties)
$m_{t\bar{t}} < 450$ GeV	1.11 ± 0.04 ± 0.13	0.85 (0.84)
$450 < m_{t\bar{t}} < 550$ GeV	1.17 ± 0.09 ± 0.14	1.00 (0.91)
$550 < m_{t\bar{t}} < 800$ GeV	1.60 ± 0.24 ± 0.35	1.43 (1.37)
$m_{t\bar{t}} > 800$ GeV	2.2 ± 1.8 ± 2.3	0.41 (0.40)
inclusive	1.250 ± 0.026 ± 0.063	3.70 (3.20)

- No MC can describe the data

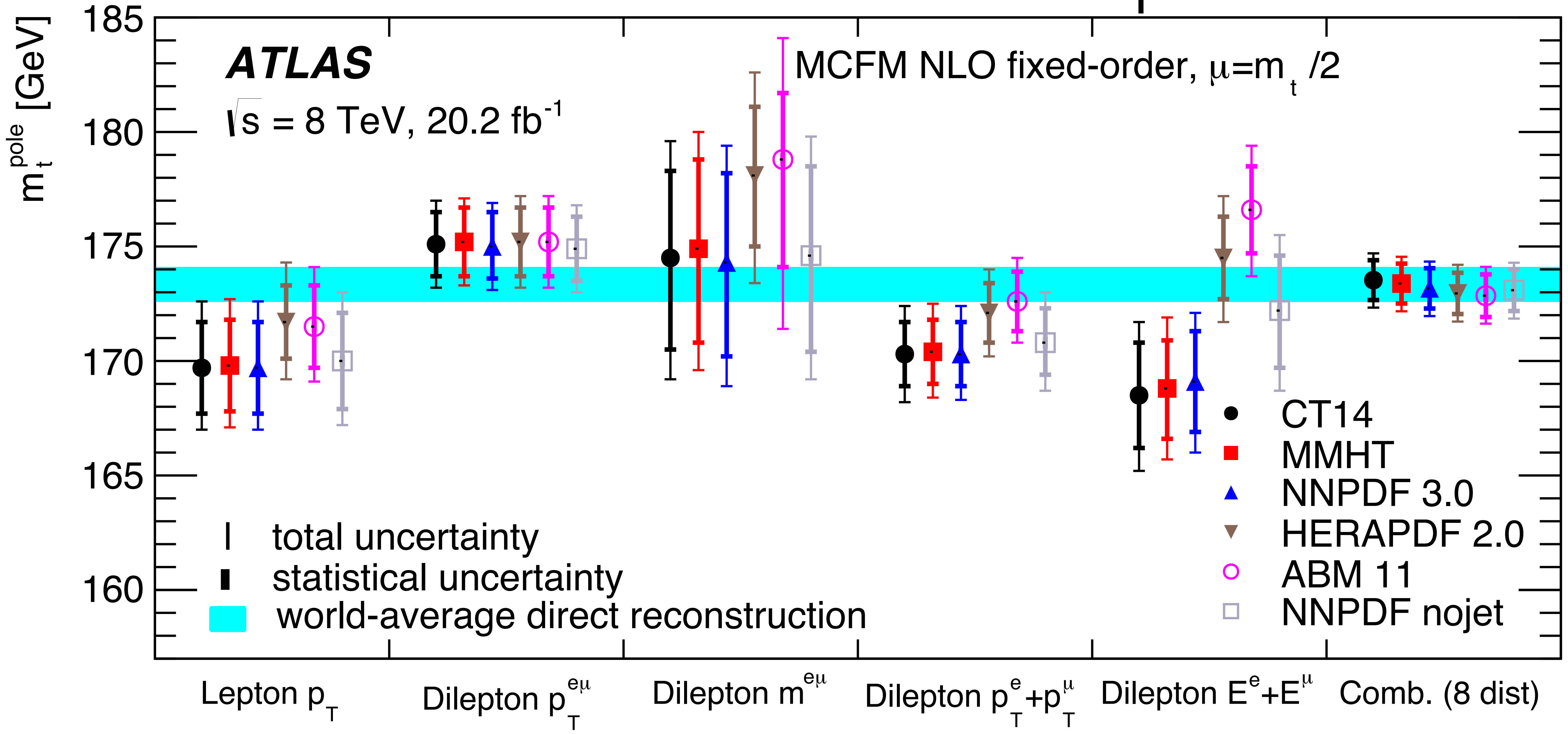
Summary

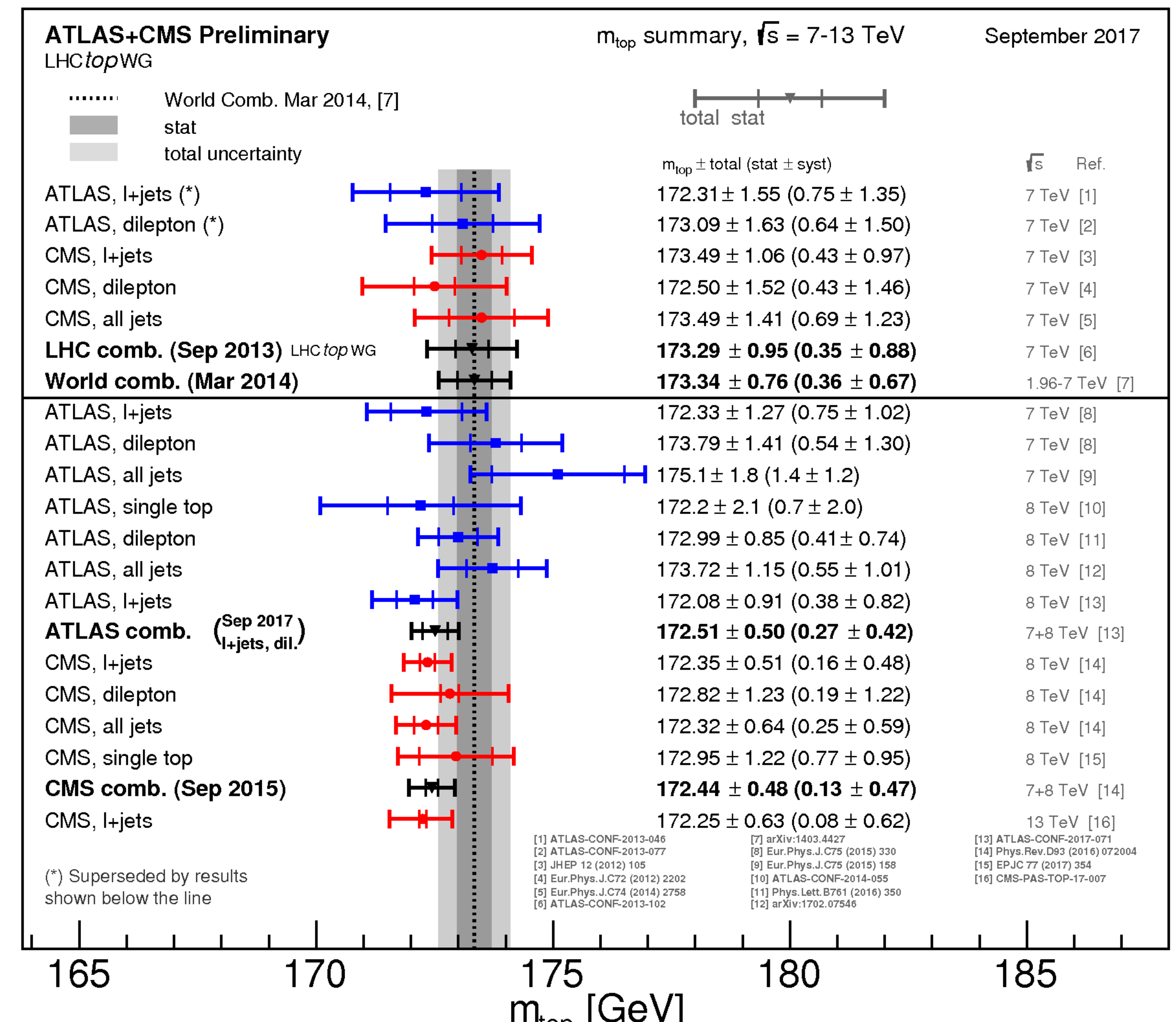
- The top quark is interesting and unique
- Provides a laboratory for testing theory predictions and performing high-precision measurements
- Window into BSM physics, possible future directions
- A significant part of ATLAS research programme
- Lots of recent activity with interesting results
- Modelling will improve, more data brings more results

Backup

Top mass

Pole mass from fixed-order predictions

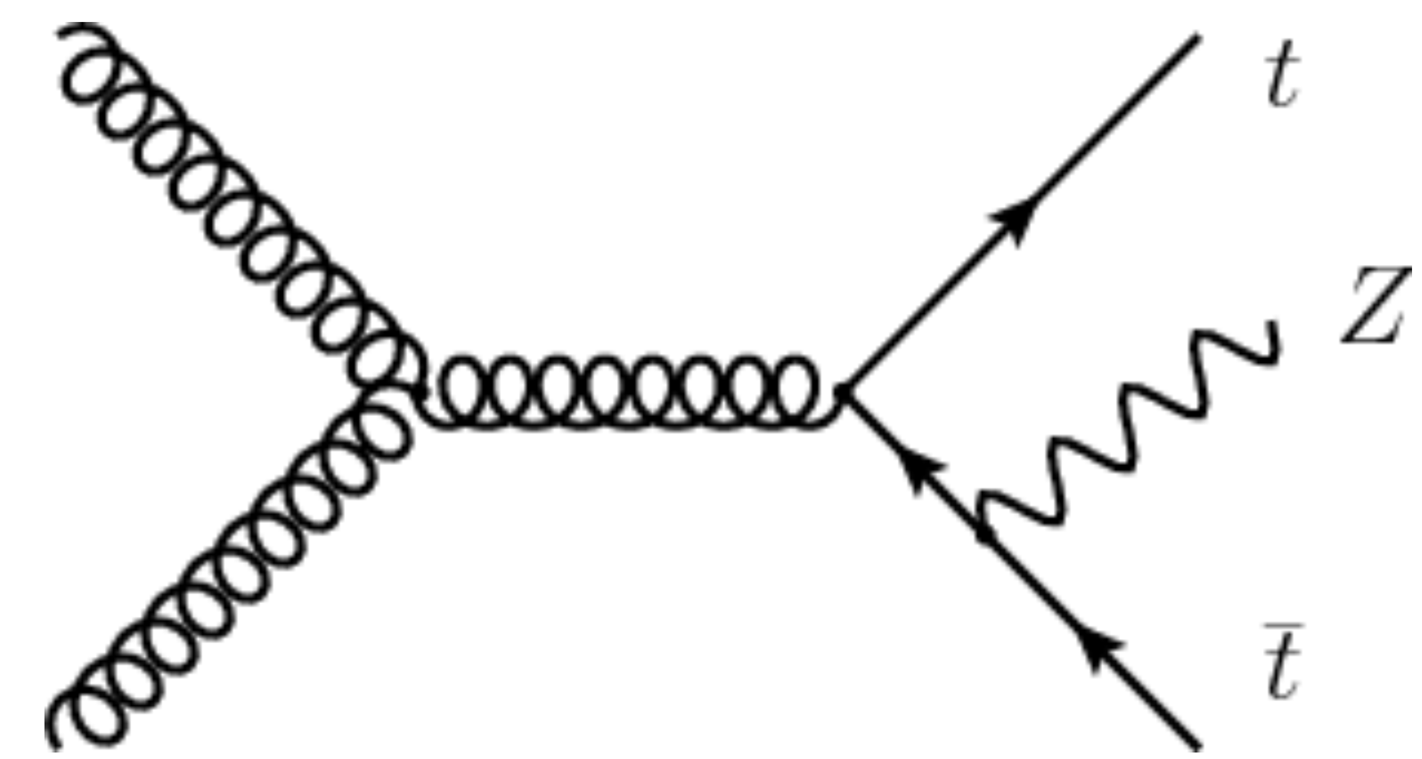


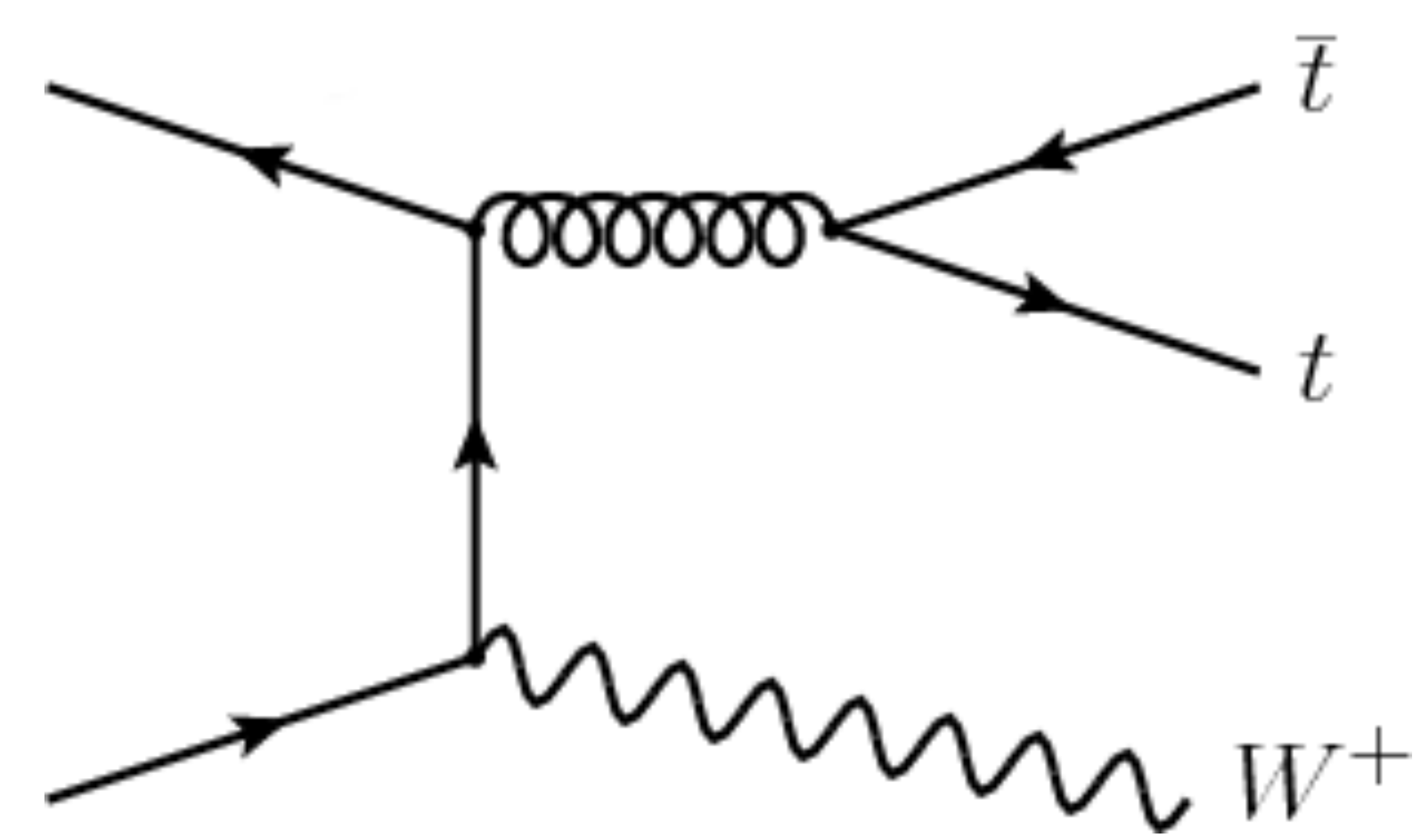


- 8 TeV <u>all-hadronic</u>: ≥ 6 jets, ≥ 2 b-tags, event reconstruction with χ^2, measure $R_{32} = m_{jjj} / m_{jj}$
  Result: 173.72 ± 0.55 (stat.) ± 1.01 (syst.) GeV
- 8 TeV <u>lepton+jets</u>: large uncertainties in JES reduced by simultaneously fitting (b)JSF, kinematic likelihood fit in BDT and select well-reconstructed events
  Result: 172.08 ± 0.39 (stat) ± 0.82 (syst) GeV

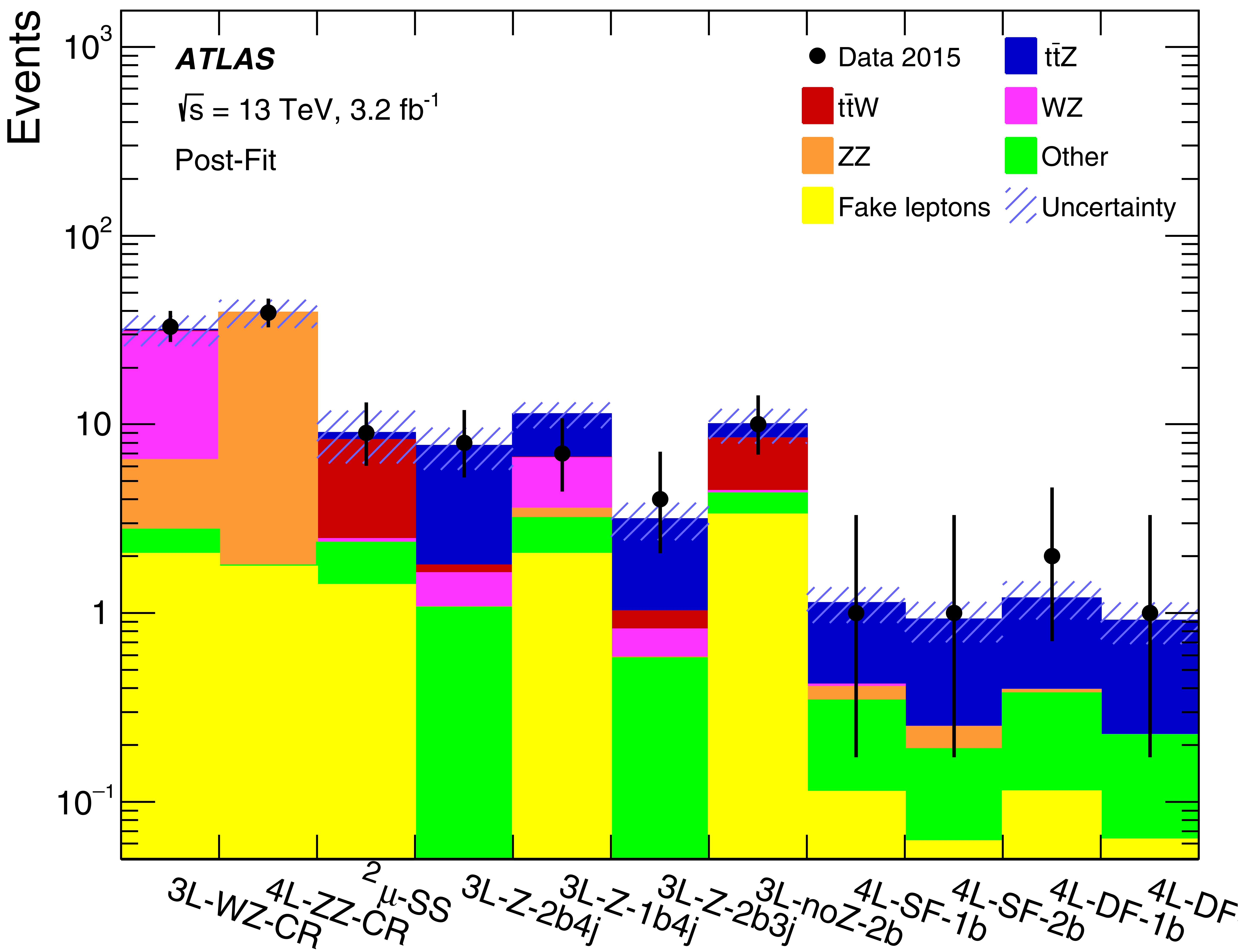
ttW and ttZ cross sections

- Motivation: sensitive to BSM physics (vector-like quarks, extra Higgs), precision test of SM, top quark coupling to weak neutral current (ttZ)
- Link to paper, 3.2 fb^{-1} @ 13 TeV (first at this energy)
- Analyses in 2x, 3x, 4x lepton channels
- Analysis strategy: define many regions by N_{jets} and $N_{\text{b-tags}}$ and label them…
    - Validation: check fake estimation (not in fit)
    - Control: diboson normalisations (in fit)
    - Signal: either ttW, ttZ
- Fit control and signal regions simultaneously

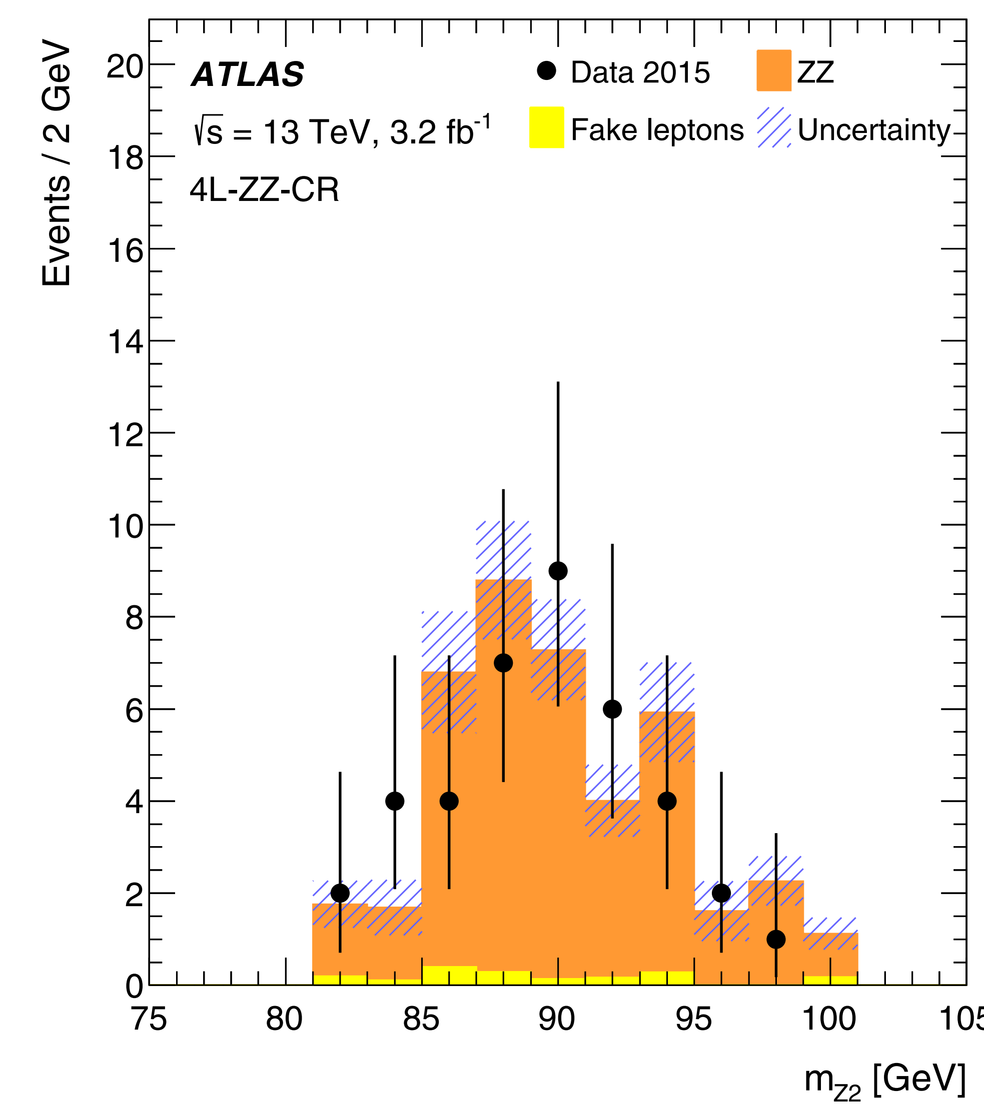




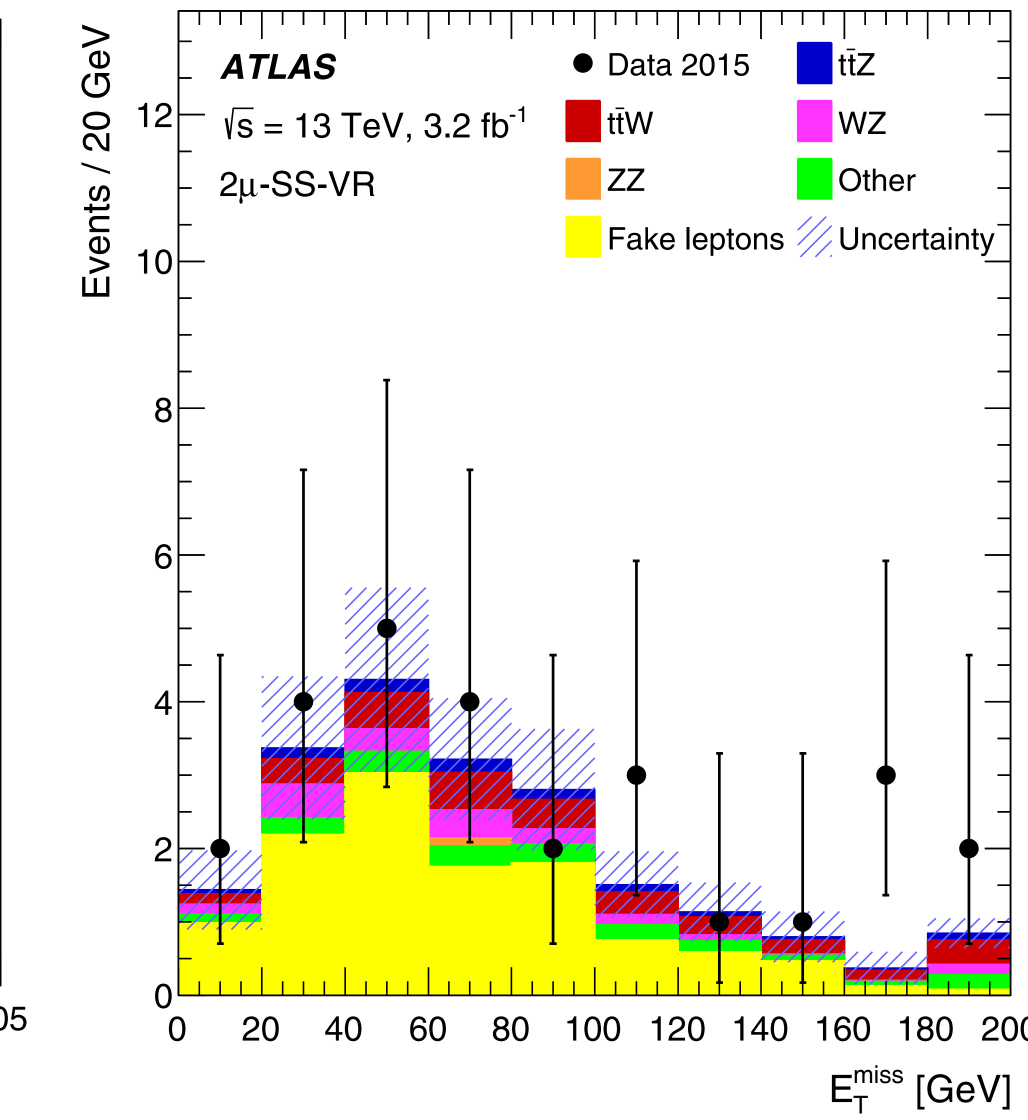
ttW and ttZ cross sections — control, validation, signal regions



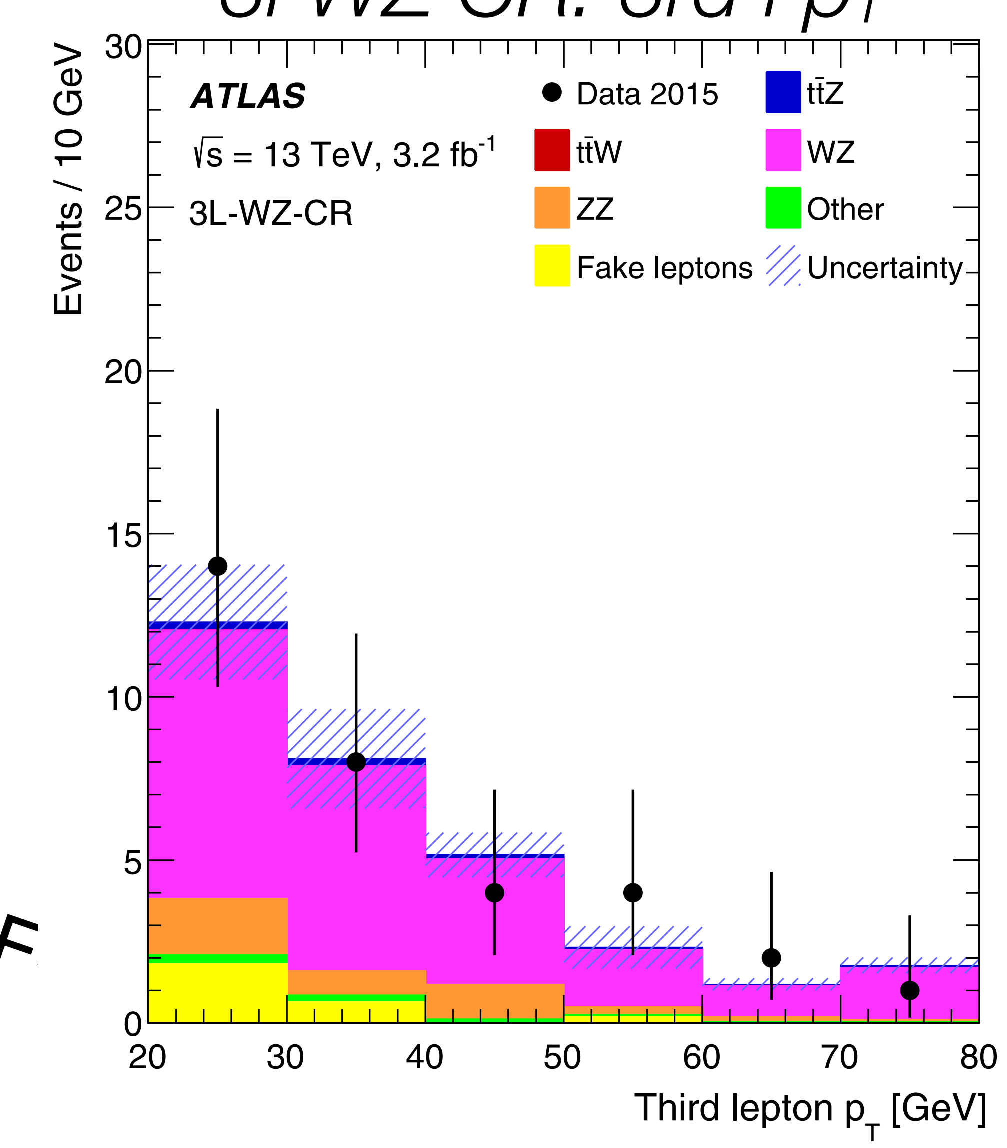
4l ZZ CR: m_Z



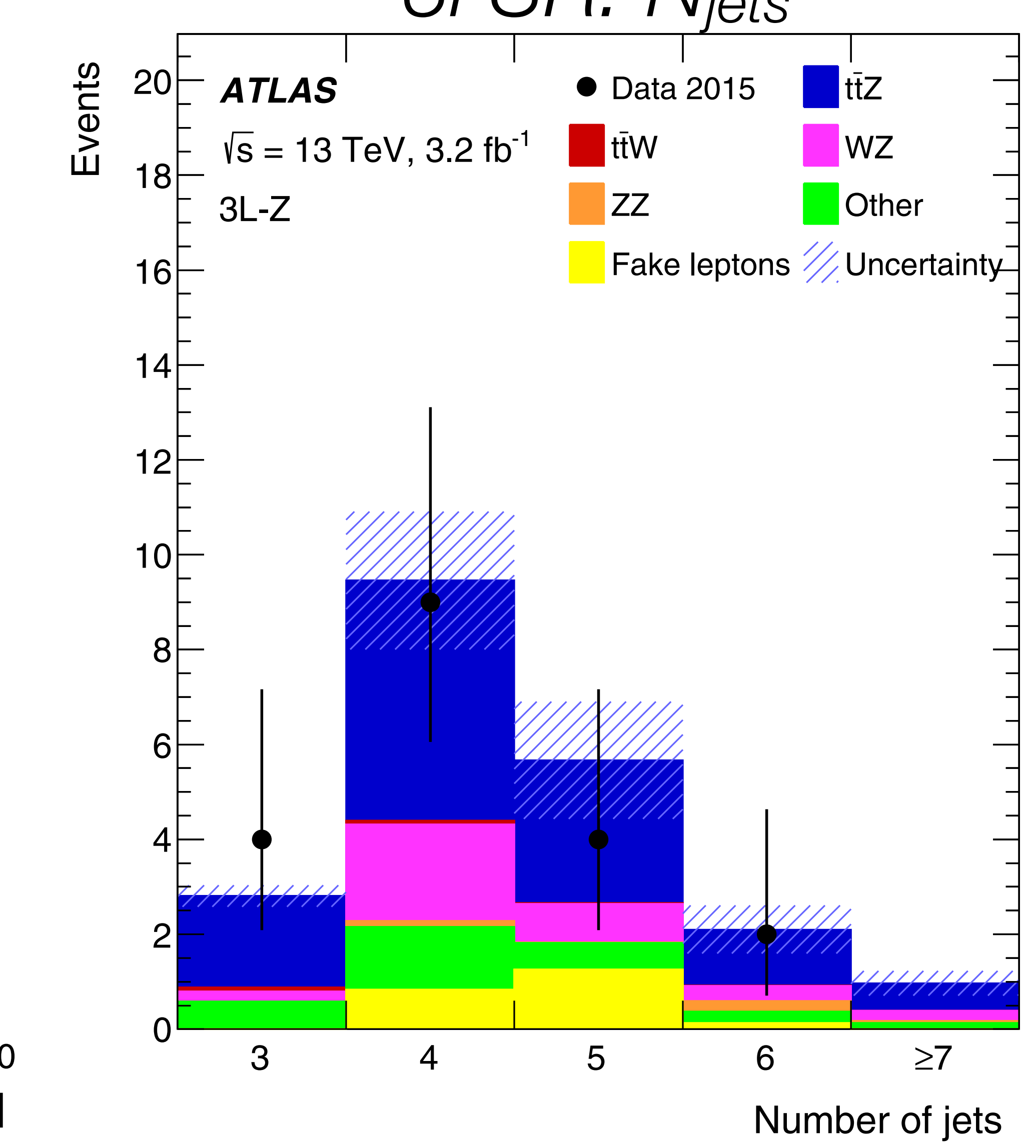
2μ(SS) VR: MET



3l WZ CR: 3rd l p_T



3l SR: N_{jets}

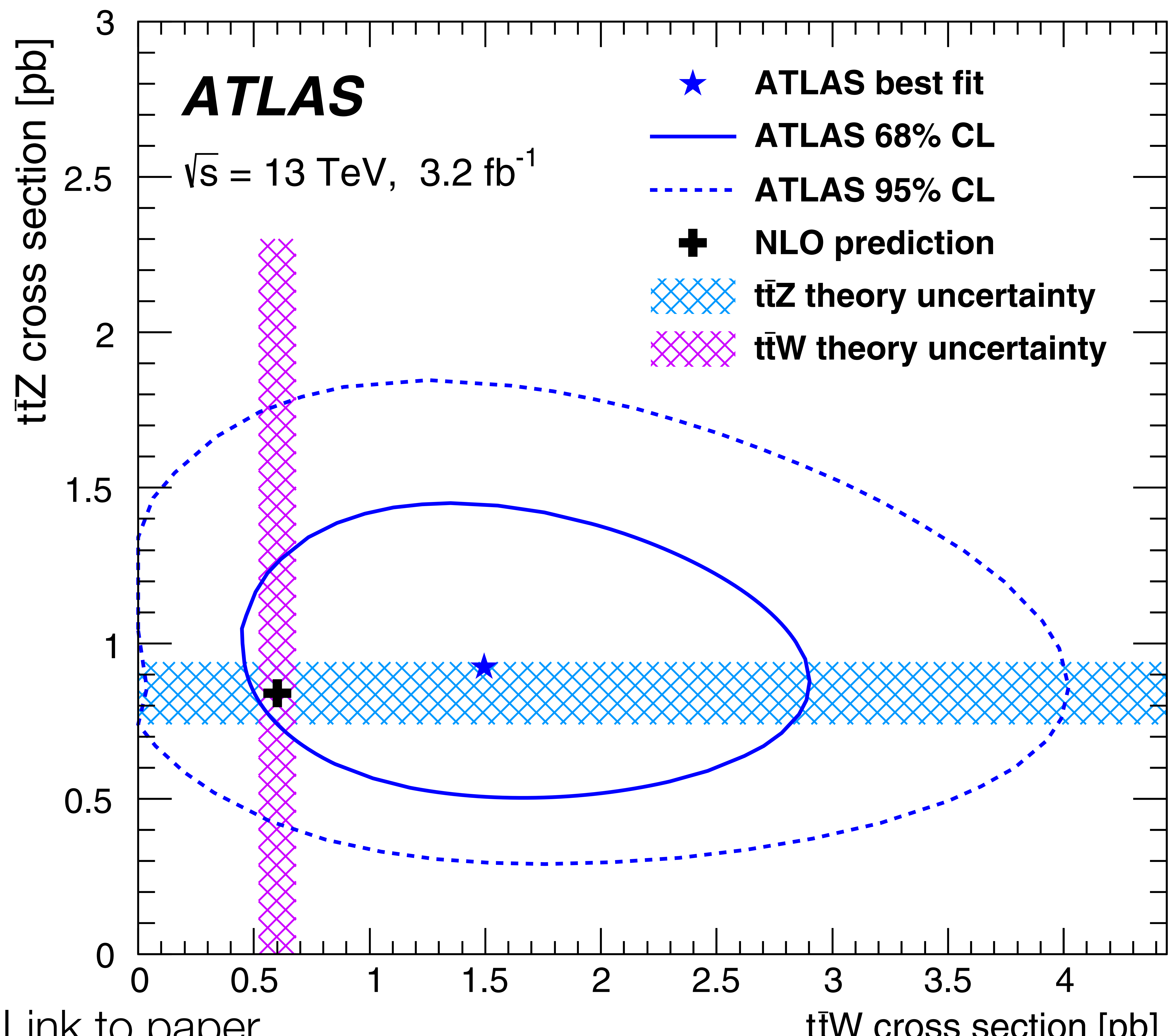


Link to paper

ttW and ttZ cross sections — fit results

Observed (expected) significance over bkg-only hypotheses:

ttW: 2.2σ (1.0σ), ttZ: 3.9σ (3.4σ)



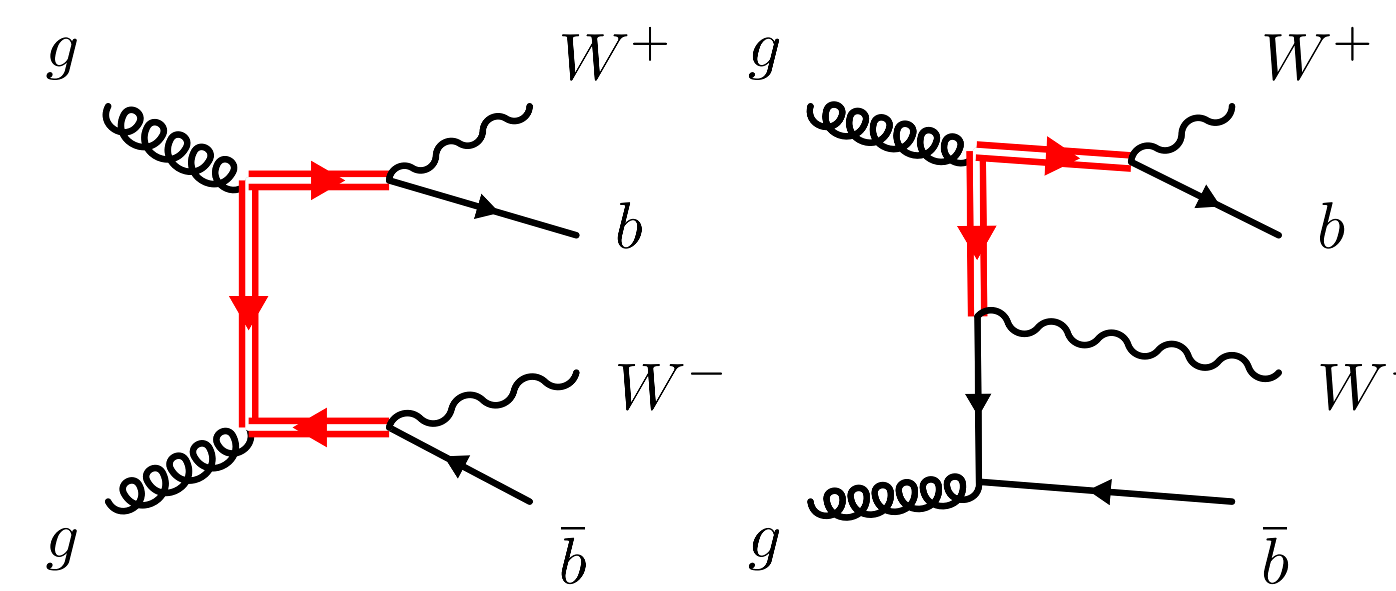
Link to paper

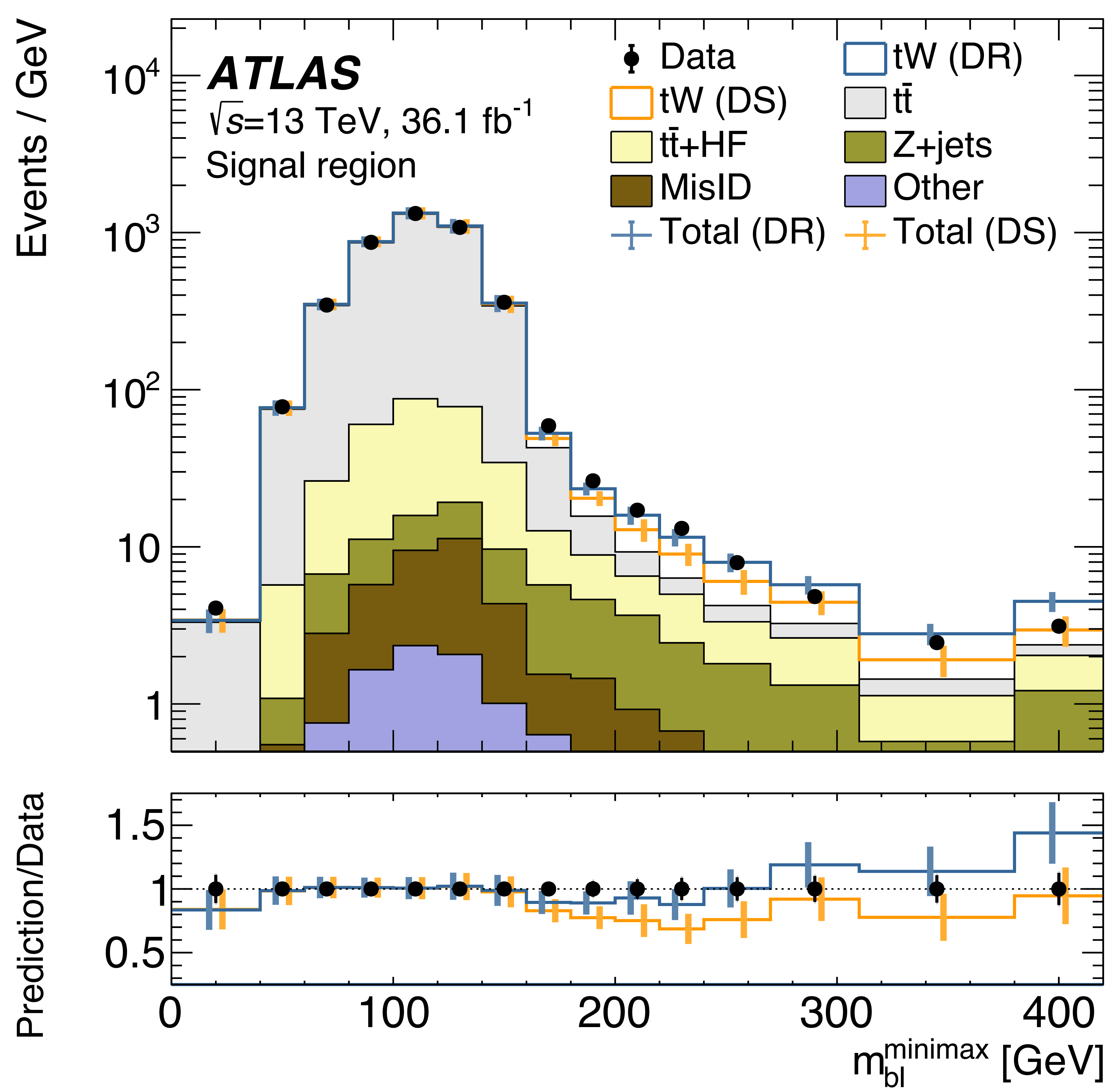
- WZ, ZZ normalisation corrections compatible with unity (WZ=1.11±0.30, ZZ=0.94±0.17)
- At 8 TeV with 20.3 fb-1, 5.0σ(4.2σ) observed for ttW(ttZ)
- This 13 TeV analysis is statistically limited!

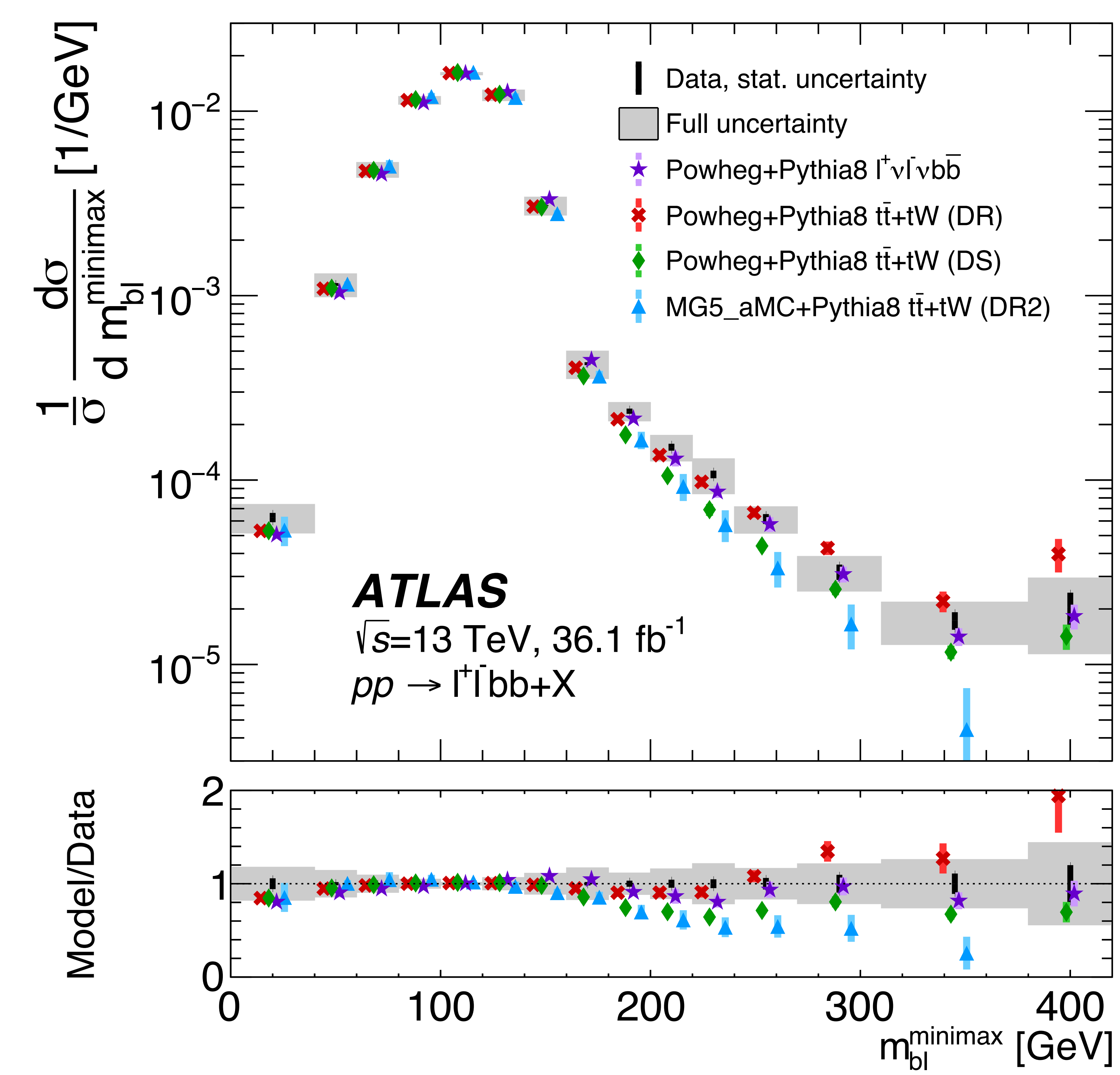
Uncertainty	$\sigma_{t\bar{t}Z}$ (%)	$\sigma_{t\bar{t}W}$ (%)
Luminosity	2.6	3.1
Reconstructed objects	8.3	9.3
Backgrounds from simulation	5.3	3.1
Fake leptons and charge misID	3.0	19
Signal modelling	2.3	4.2
Total systematic	11	22
Statistical	31	48
Total	32	53

tt/t interference

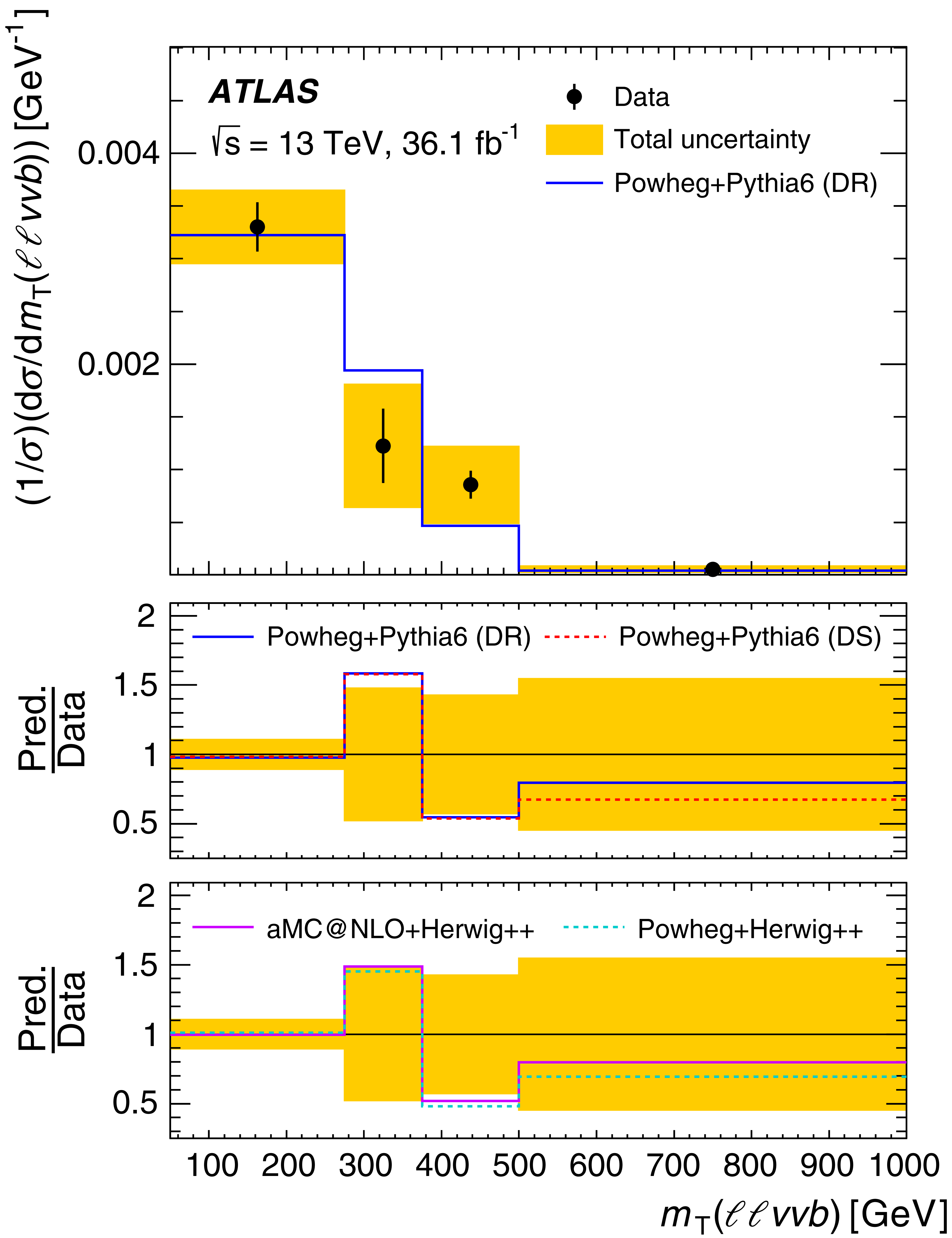
- Link to letter, 36.1 fb^{-1} @ 13 TeV
- Final state: l+l-, b-jets, MET
- Charged lepton used as proxy for W
- Mass of Wb pairs used: $m_{bl}^{\text{minimax}} \equiv \min\left[\max\left(m_{b_1 l_1}, m_{b_2 l_2}\right), \max\left(m_{b_1 l_2}, m_{b_2, l_1}\right)\right]$

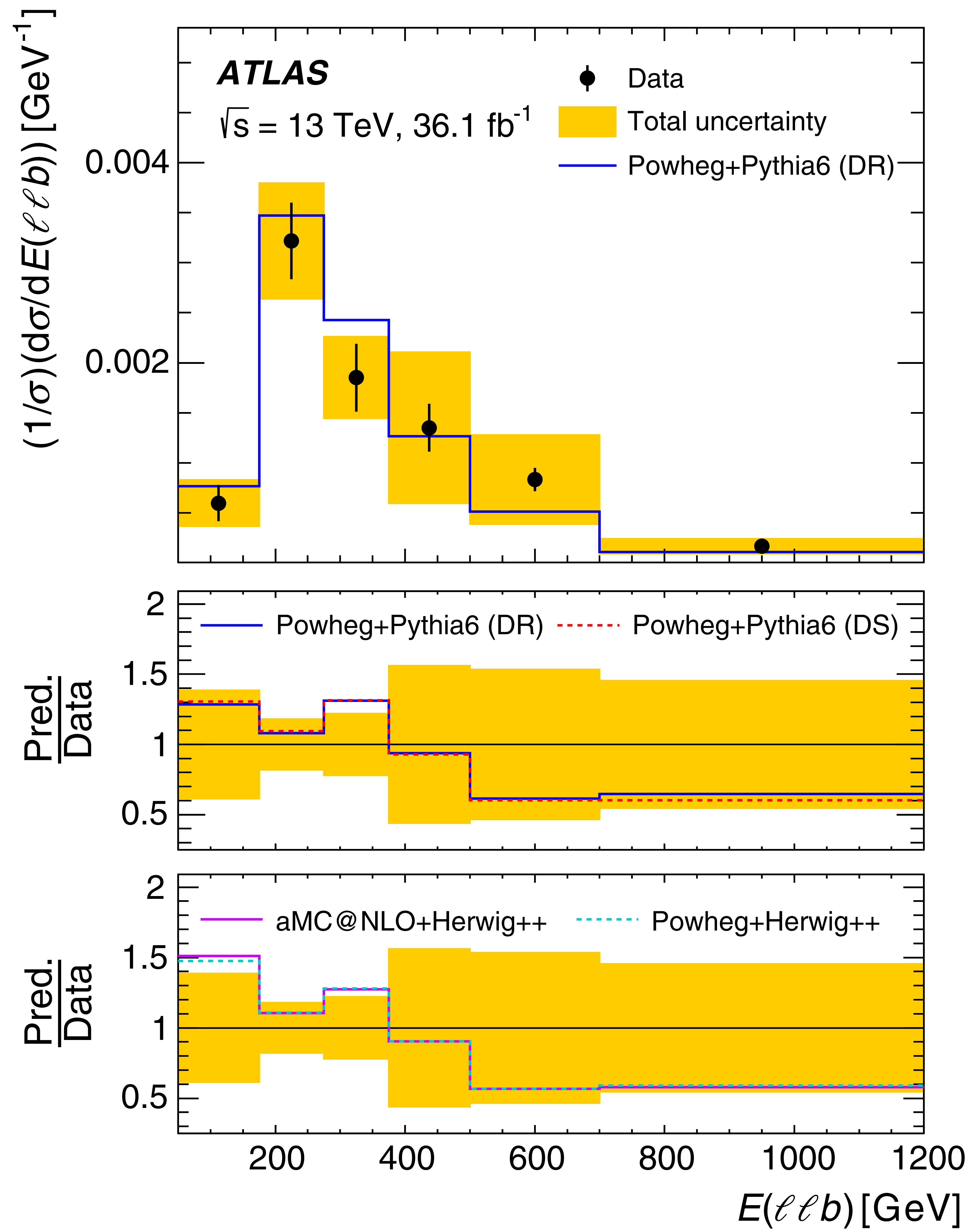




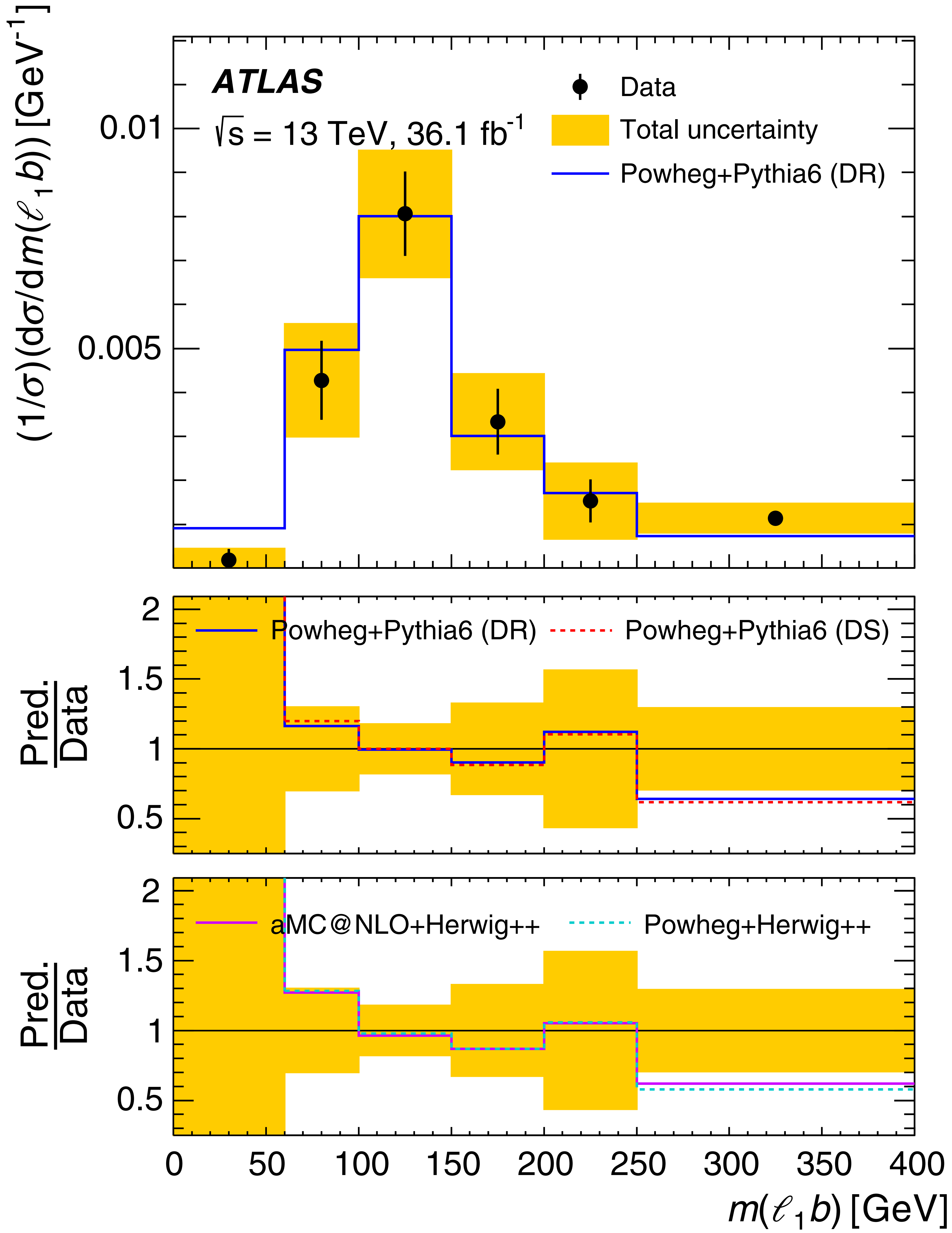


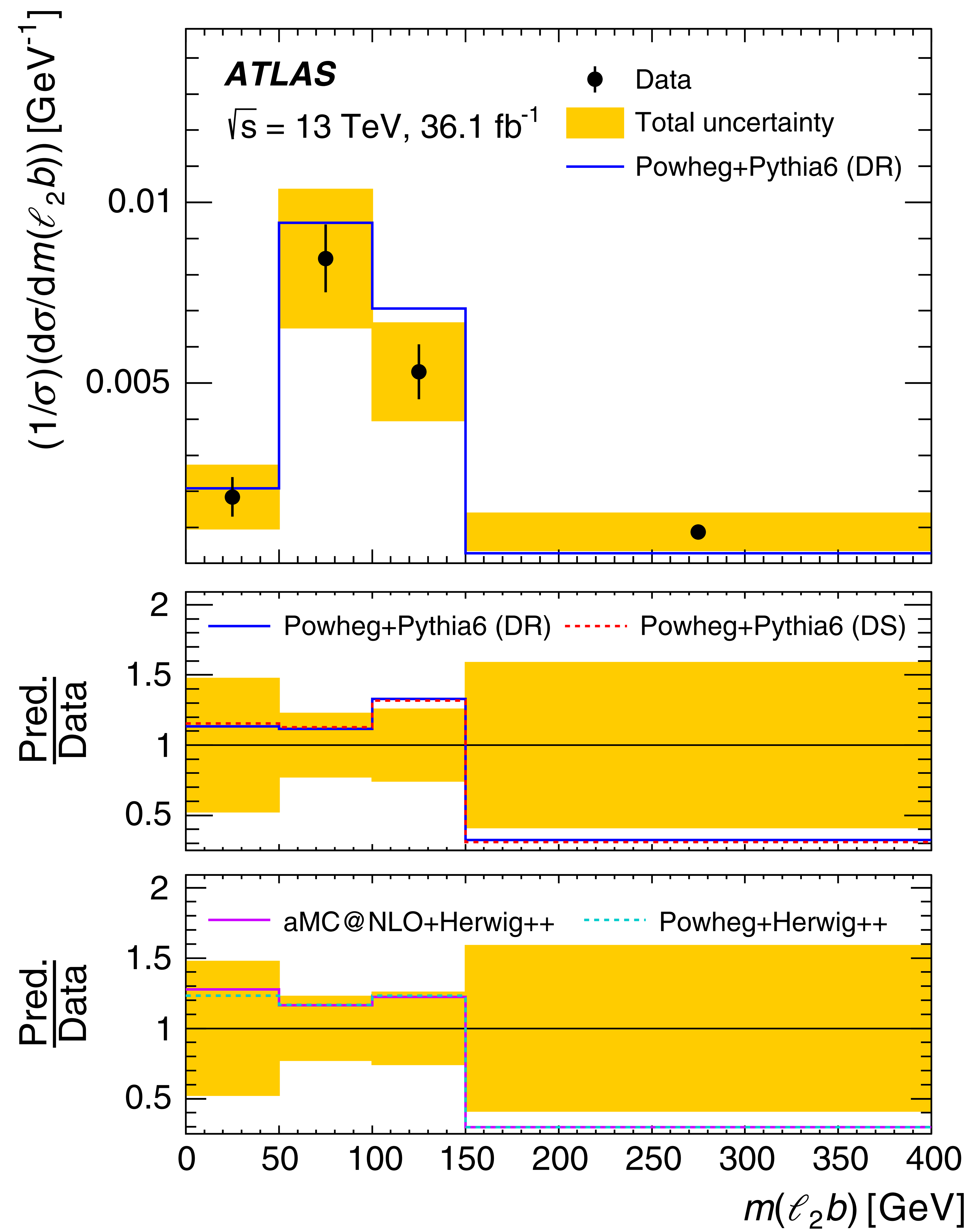
tW — more results





tW — more results





tZ — Neural network inputs

Table 2
Variables used as input to the neural network, ordered by their separation power.

Variable	Definition
$\|\eta(\mathrm{j})\|$	Absolute value of untagged jet η
$p_\mathrm{T}(\mathrm{j})$	Untagged jet p_T
m_t	Reconstructed top-quark mass
$p_\mathrm{T}(\ell^W)$	p_T of the lepton from the W-boson decay
$\Delta R(\mathrm{j}, Z)$	ΔR between the untagged jet and the Z boson
$m_\mathrm{T}(\ell, E_\mathrm{T}^\mathrm{miss})$	Transverse mass of W boson
$p_\mathrm{T}(t)$	Reconstructed top-quark p_T
$p_\mathrm{T}(b)$	Tagged jet p_T
$p_\mathrm{T}(Z)$	p_T of the reconstructed Z boson
$\|\eta(\ell^W)\|$	Absolute value of η of the lepton coming from the W-boson decay